CARBONATION OF CONCRETE BRIDGE STRUCTURES IN THREE SOUTH AFRICAN LOCALITIES

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of Cape Town, in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering.

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DECLARATION

I, Wood Kuen Yam, hereby declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of Cape Town. It has not been submitted before for any degree or examination in any other University.

Signed by candidate

Wood Kuen Yam

Dated this 27th day of September, 2004.

ABSTRACT

The rate of carbonation for the localities of the Cape Peninsula, Durban (i.e. Durban – KwaZulu Natal South Coast) and Johannesburg (i.e. the motorway system and between Heidelberg Road and Geldenhuis interchanges on the N3 freeway) were studied in order to derive carbonation prediction models for each of these localities. The derivation of the prediction models was based on field carbonation data measured from approximately 30 in-service bridges in each locality. One of the uses of the derived models was to allow the preparation of maintenance plans so as to avoid carbonation-induced corrosion for structures in these localities.

Since the rate of carbonation depends strongly on material and environmental factors, the carbonation data from each locality were analysed separately on the grounds that these localities have different climatic conditions. The data within each locality represent different material and exposure conditions, and the data were therefore grouped according to the concrete strength grade (as a measure of concrete quality) and exposure conditions, prior to statistical analysis. Based on the method of least squares, as well as integration of the understanding of the process of carbonation and knowledge of climatic conditions of each locality, carbonation prediction models for a variety of concretes for each locality were derived.

Results show that bridge structures in the Johannesburg locality have the highest carbonation rate due to the relatively dry environment throughout the year. Bridges in Durban locality exhibit a lower carbonation rate than Johannesburg bridges, but higher than Cape Peninsula bridges owing to shorter rainfall duration and higher temperature.

In addition, the carbonation rates of both exposed and sheltered elements with similar concrete strength grades for bridges in Durban are very similar, i.e. exposure condition has little influence on carbonation rate for these elements. The same is true for bridges in the Johannesburg locality. It is surmised that short precipitation times and high relative humidity in Durban locality make the near surface moisture content

of exposed and sheltered elements very similar. Likewise, it is surmised that short rainfall duration and low relative humidity in Johannesburg locality result in essentially the same near surface moisture content of concrete elements throughout the exposure time.

The data in Durban locality show that old concretes have a slower carbonation rate than modern concretes with the same concrete strength grade. This is likely due to the changes in cement properties over the years, related to the need for fast track development for modern structures. This finding indicates that the prediction models are not suitable for carbonation predictions for future structures (produced by modern cements) as the rates of carbonation will be different.

Oxygen Permeability Index (OPI) was investigated in an attempt to predict the rate of carbonation. According to the philosophy and testing procedures for OPI, it is considered that early age OPI may be superior to concrete strength grade for carbonation predictions because of better characterisation of the permeability of (cover) concrete. However, due to the lack of early age OPI information for the data, using OPI as a carbonation prediction tool was not entirely successful. Further research in this regard is worthwhile.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Corrosion of embedded steel reinforcement is the main cause of many reinforced concrete structures exhibiting unacceptable levels of deterioration. In simple terms, these structures are badly cracked and very often spalling of cover concrete has occurred.

Concrete itself offers a very good environment which can protect the embedded steel reinforcement from corroding due to the provision of a high alkaline environment afforded by the pore solution. In this high alkaline environment, a passive layer is formed on the steel surface. Because of this impermeable passive layer formed on the steel reinforcing, active corrosion will not take place even in the presence of both moisture and oxygen.

However, this passive layer may become unstable in certain circumstances. A common circumstance when this passive layer breaks down is when the surrounding environment (i.e. the pore solution) becomes less alkaline.

Carbonation of concrete is a common chemical reaction within concrete which reduces the alkalinity of the pore solution, thus causing depassivation of the reinforcement. Corrosion of steel reinforcement will start when moisture and oxygen are present, after which products of corrosion are formed. The formation of the expansive corrosion products causes cracking and spalling of the cover concrete. Hence, the structural and aesthetic aspects of the structure are largely compromised.

Many reinforced concrete structures in South Africa and around the world show signs of distress owing to carbonation-induced corrosion. Consequently, high repair and rehabilitation costs to these damaged structures result.

In South Africa, a contributing factor from the design perspective may be a lack of information on the rate of carbonation. This can be attributed to the absence of reliable and proven carbonation prediction models for South African conditions.

The derivation of reliable models for carbonation prediction in South Africa is difficult as the access of good data of carbonation from South African structures is very limited. Without carbonation data, the derivation of carbonation prediction models is not possible.

With these limitations, the design of durable reinforced concrete structures against carbonation-induced corrosion cannot be achieved. Therefore, this research is committed in an attempt to help address these limitations.

1.2 OBJECTIVES

The objectives of this research are four-fold. The first objective involves the study of the material and environmental factors which can affect the rate and depth of carbonation of concrete. After the understanding of these factors, allowances can be made to both in-service and future structures, whereby carbonation-induced corrosion can be avoided.

The second objective is the construction of a carbonation information database for South African structures. This database can eventually be built up to contain a wealth of carbonation data from many reinforced concrete bridges and other structures in South Africa. This database should also contain necessary information such as year of construction and exposure conditions. It could be used for the analysis of the rate and the depth of carbonation and hence to derive a carbonation prediction model.

The prediction models derived in this research could be improved by the continual gathering and analysis of new carbonation data from field concrete structures.

Thirdly, analytical methods to analyse the carbonation data in the database are proposed. The provision of procedures for and comments on these methods allows future work on the analysis of new data to improve the prediction models derived in this research, as well as the derivation of "new" prediction models which predict the performance of modern cements for future structures.

The fourth objective is to derive suitable carbonation prediction models obtained from different methods of analysis, for maintenance and design. From these prediction models, maintenance plans and sourcing of funds for in-situ structures can be organised in advance; on the other hand, the necessity of the provision of sufficient depth of cover to the reinforcement for the prevention of carbonation-induced corrosion for future structures, as well as the implications of the changes in materials can be addressed.

1.3 SCOPE OF THIS RESEARCH

Carbonation data and the carbonation prediction models derived in this research are limited to the Cape Peninsula*, Durban† and Johannesburg‡ localities only. This is because field data of carbonation were obtained from these three localities.

Statistical methods are employed to analyse the obtained data and seek to understand the rates and depth of carbonation. The derivation and explanation of the statistical methods employed are provided briefly in this thesis.

* Cape Peninsula locality: the central, northern and south-eastern parts of the Cape Peninsula
† Durban Locality: Durban – KwaZulu Natal South Coast along the N2 freeway
‡ Johannesburg locality: Johannesburg Motorway System, and on the N3 freeway between Heidelberg Road and Geldenhuis interchanges

1.4 METHODOLOGY

The most appropriate way to derive carbonation prediction models which can reflect the effects of the material and environmental conditions on concrete structures in different localities, is to measure the depth of carbonation from field structures in these localities. Therefore, carbonation data were obtained from in-situ bridge structures in the Cape Peninsula, Durban and Johannesburg localities, and were used to derive carbonation prediction models.

The data are grouped into subdivisions according to the equivalent concrete compressive strengths at 28 days and exposure conditions. For each subdivision, two commonly used analytical methods are employed to analyse the data. Hence the most suitable carbonation prediction model for the obtained data is selected for each condition, based on both statistical principles and the understanding of the process of carbonation under the given exposure conditions.

1.5 PLAN OF DEVELOPMENT

This thesis considers the process of carbonation, and involves the derivation of carbonation prediction models in order to inform maintenance plans for in-service structures. The presentation of this investigation is as follows:

Chapter 2 gives a broad introduction to the corrosion of steel reinforcement. It enriches the reader with knowledge on the understanding of corrosion of steel reinforcement in concrete. It consists of the fundamental aspects of reinforcement corrosion, including the mechanisms, the governing factors as well as the structural, aesthetic and economic consequences of structures suffering from reinforcement corrosion.

Chapter 3 focuses on the process of carbonation of concrete in more detail. It discusses the reactions involved in carbonation, factors that affect the rate of carbonation, as well as several existing carbonation prediction models which have been derived elsewhere using different materials and under different environments.

Chapter 4 studies the climatic conditions of the Cape Peninsula, Durban and Johannesburg localities, which can give a general idea of the rate and depth of carbonation of structures in these localities. In addition, the chapter provides a database of the obtained carbonation field data for each of these localities.

Chapter 5 subdivides the obtained field data in terms of grade and exposure conditions in the database. Two methods are employed to analyse the data and hence a carbonation prediction model is derived for each subdivision. Based on statistical principles, as well as understanding of the process of carbonation and the climatic conditions of these localities, a suitable carbonation prediction model can be selected for each subdivision in each locality.

Chapter 6 introduces another parameter which can be used as an indicator of the rate of carbonation. This indicator is Oxygen Permeability Index (OPI). OPI is regarded as a superior indicator to concrete strength grade, since OPI measures the gaseous permeability of concrete which relates to the diffusion of carbon dioxide. The depth of carbonation may be correlated to the OPI. Hence a carbonation prediction model based on OPI can be obtained. Detail discussion in this aspect will be provided.

Chapter 7 concludes the work that is done in this research, and recommends future work that can be considered in the understanding of carbonation of concrete in South Africa. A list of references then follows. Finally the statistical approaches employed and other detailed information are presented in the appendices.

CHAPTER 2

CORROSION OF STEEL REINFORCEMENT

2.1. INTRODUCTION

Concrete provides a high alkaline environment afforded by the pore solution, leading to a tightly adhering passivation layer surrounding the embedded steel reinforcement. This passivation layer effectively protects the steel reinforcement from corrosion even in the presence of oxygen and moisture. Concrete with low permeability can also be an effective way to prevent corrosion of the embedded steel reinforcement. Low permeability can minimize the ingress of corrosion-inducing agents such as carbon dioxide, as well as increase the electrical resistivity of concrete against the electrochemical process of corrosion.

However, if the concrete is not designed properly for the service environment and an appropriate design life, depassivation of steel reinforcement can occur and initiates corrosion. After that, the steel reinforcement is vulnerable to corrosion when oxygen and moisture are both present, and corrosion propagates as illustrated in Figure 2.1 (Tuutti (1982)). In many cases, the corrosion of steel reinforcement leads to very serious structural and aesthetic consequences.

This chapter first introduces the mechanism of corrosion of steel reinforcement after depassivation. In the following chapter, a detailed discussion of depassivation caused by carbonation of concrete will be provided as carbonation of concrete is the focus of this research. Secondly, this chapter briefly discusses the governing factors of corrosion for both initiation and propagation. Thirdly, it highlights corrosion-related consequences for concrete.

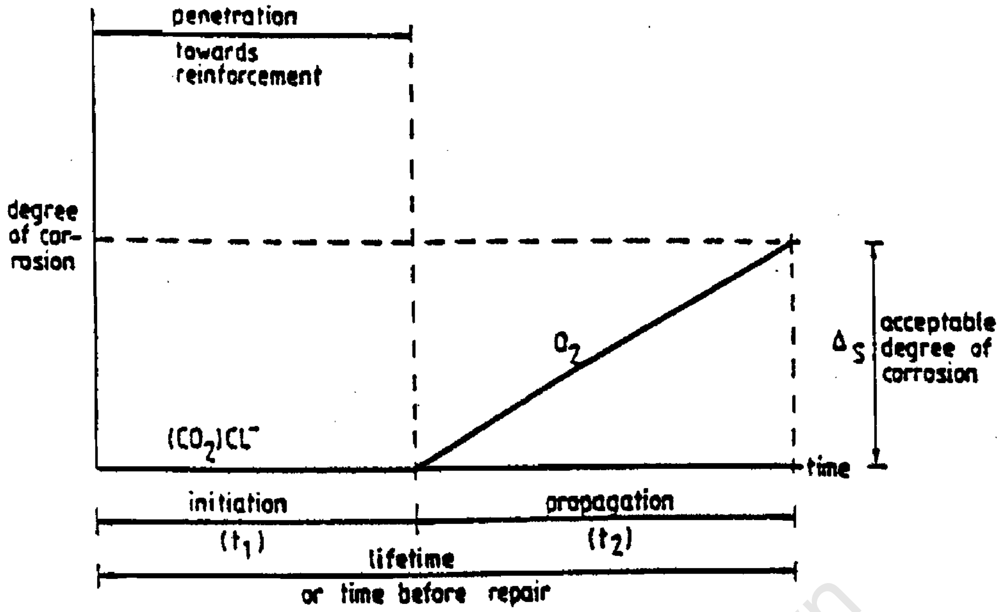


Figure 2.1: Relationship between the initiation and propagation periods in the deterioration of concrete structures. (Tuutti (1982)).

2.2. FUNDAMENTALS OF REINFORCEMENT CORROSION

2.2.1 Mechanism of Corrosion

Corrosion of embedded steel reinforcement is an electrochemical process, in which oxidation of iron (to form ferrous ions) occurs at the anode while reduction of oxygen (to form hydroxyl ions) takes place at the cathode. (ACI Committee 222 (2003)).

The surface of corroding reinforcement comprises both anodes and cathodes and is electrically connected through itself. The surrounding pore water solution can act as an aqueous medium for the movement of ions. Figure 2.2 shows the mechanism of corrosion schematically (Mackechnie (2001)).

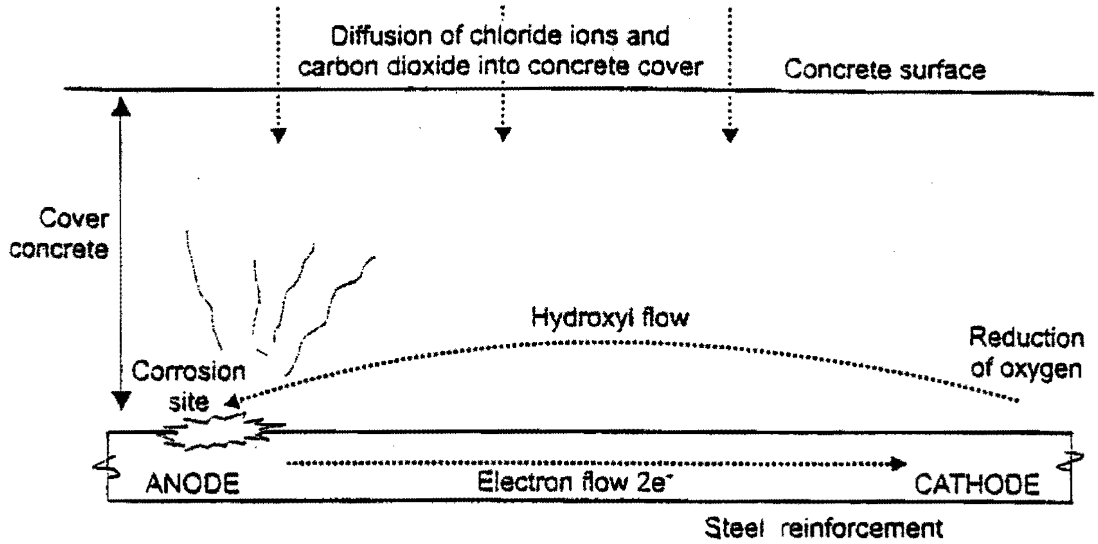


Figure 2.2: Schematic of corrosion of steel in concrete (Mackechnie (2001)).

Bouwer (1998) reported that the formation of anodes and cathodes on the surface of the reinforcement is due to the electrochemical potential differences along its surface. The variations in the concentration of dissolved ions of alkalis, chlorides and oxygen cause these electrochemical potential differences and result in the formation of anodic areas and cathodic areas.

The dissolution of iron or oxidation occurs at the anode. The anodic reaction can be expressed as follows:

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad (2.1)$$

Iron ions enter the pore solution and liberate two electrons per ion.

Reduction occurs at the cathode. The electrons liberated from the anode move to the cathode via the steel reinforcement. These electrons react with the oxygen and moisture that penetrate the concrete to the cathode and this reaction can be expressed as follows:

$$2e^- + \frac{1}{2} O_2 + H_2O \rightarrow 2(OH)^- \qquad (2.2)$$

Hydroxyl ions are formed in this cathodic reaction. These hydroxyl ions then migrate to react with the ions of iron in the pore solution and form the products of corrosion. The reaction is shown below:

$$Fe^{2+} + 2(OH)^{-} + \tfrac{1}{4} O_2 + \tfrac{1}{2} H_2O \rightarrow Fe(OH)_3 \qquad (2.3)$$

The products of corrosion are generally deposited near the anode (Raupach (1996)). The volume of products of corrosion formed is several times that of the original steel reinforcement. This increase in volume can lead to serious cracking and spalling of the concrete and this aspect will be discussed later. Figure 2.3 shows the stages in corrosion-induced damage (Richardson (2002)).

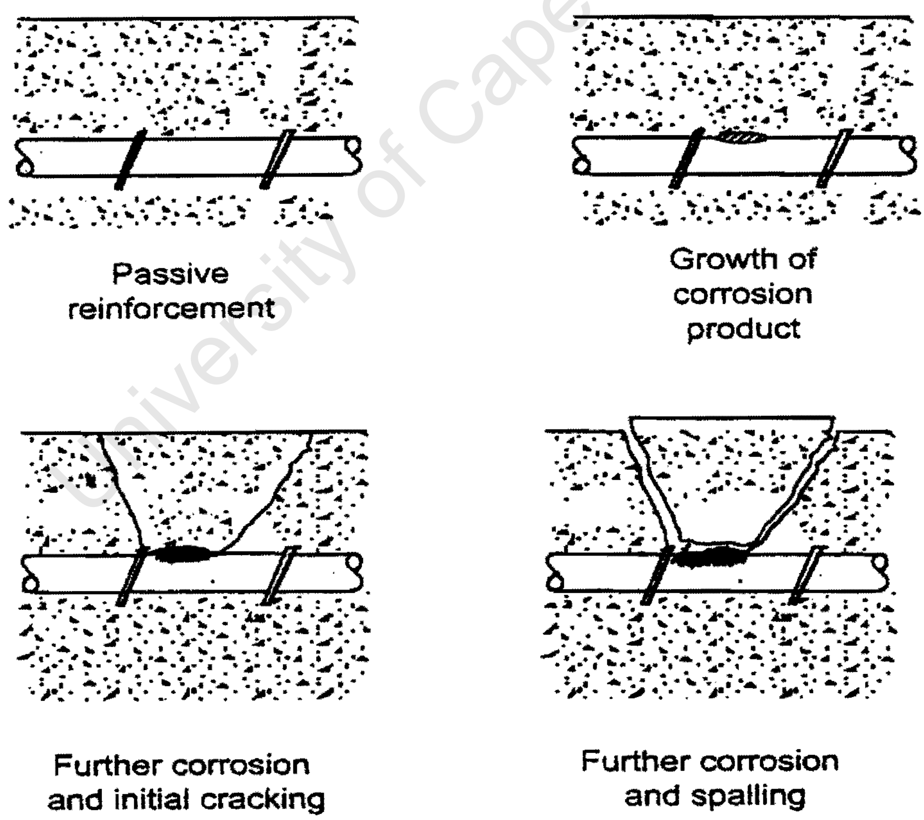


Figure 2.3: Stages in corrosion-induced damage (Richardson (2002)).

2.2.2 Common Forms of Corrosion

2.2.2 (a) General Corrosion

General corrosion of steel is where multiple pits are formed on the steel surface (Mackechnie and Alexander (2001)) and hence the majority of steel is corroded (Treadaway (1988)). This is typically due to the overall depassivation of steel caused by the process of carbonation of cover concrete. Mackechnie (2004) found that, based on over 80 structural investigations including many parking garages which often have high carbonation depths, it is rare to have carbonation-induced corrosion with cover concrete greater than 25 mm as conditions are too dry (i.e. lack of moisture) because generally and periodic wetting does not penetrate to such depths.

2.2.2 (b) Pitting Corrosion

Pitting corrosion is caused by the effect of chloride ions. In the presence of sufficient quantities of chloride (nominally taken as 0.4% or more by mass of cement), the passive layer of reinforcement will be disrupted only over a small area, thus forming a small anodic area where dissolution of iron takes place. This leads to serious localized pitting corrosion. Figure 2.4 shows the mechanism of pitting corrosion schematically (Treadaway (1988)).

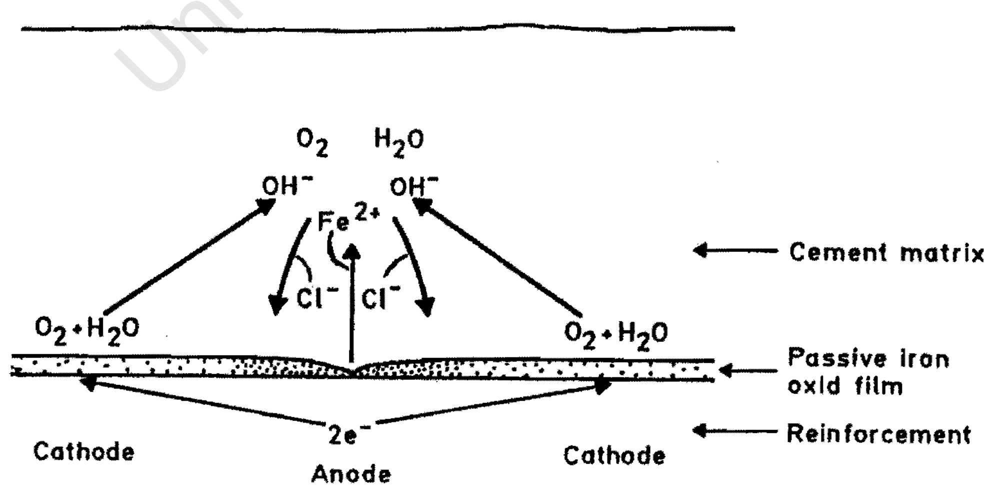


Figure 2.4: Pitting corrosion caused by chloride ions (Treadaway (1998)).

2.3. FACTORS GOVERNING REINFORCEMENT CORROSION

The corrosion of reinforcement is influenced by water/cement ratio, pH of the concrete pore solution, the action of chloride ions when they are present, temperature, external cracks in the concrete surface and the availability of oxygen and moisture.

2.3.1 Water/Cement Ratio

Water/cement ratio is a crucial factor that partly determines the permeability of concrete. Water in concrete evaporates to the environment in due course and the volume that the evaporated water previously occupied will remain as voids. If these voids are interconnected, they form a pathway for the corrosion-inducing agents to the surface of the steel reinforcement. Hence, corrosion can be initiated and propagated.

The lower the water/cement ratio, the less amount of water available to evaporate, and the less amount of voids formed. This can limit corrosion by greatly reducing the ingress of corrosion-inducing agents such as carbon dioxide and chlorides to the surface of the steel reinforcement.

2.3.2 pH of the Pore Solution

As mentioned earlier, the passive layer is stable only in the high alkaline environment, i.e. pH greater than 10.5 (Mackechnie and Alexander (2001)). This high alkaline environment can be destroyed by acidification, generally due to carbonation in normal environments. Carbonation is the reaction in which carbon dioxide reacts mainly with calcium hydroxide to form calcium carbonate, in the presence of water. This reaction is generally very slow and depends on the relative humidity of the environment, temperature, permeability of concrete and the concentration of carbon dioxide (ACI Committee 201 (2003)).

Carbonation occurs optimally at a relative humidity of between 50% and 75%. If the relative humidity is below 25%, then carbonation can be considered insignificant, whilst, above 75%, moisture in the pores significantly reduces carbon dioxide penetration (ACI Committee 201 (2003)).

The formation and deposition of calcium carbonate through carbonation of concrete reduces the pH of the pore solution. When the pH of the pore solution at the reinforcement is lowered to about 10.5 (Mackechnie and Alexander (2001)), depassivation occurs and in the presence of both oxygen and moisture, corrosion of reinforcement propagates. Carbonation of concrete will be discussed in more detail in the next chapter.

2.3.3 Action of Chloride Ions

Chlorides normally diffuse into concrete from the sources of deicing salts or seawater. They diffuse through the partially or fully saturated pores of concrete, but no diffusion can take place in dry concrete.

Moskvin (1983) stated that when the concentration of chloride ion exceeds 4 to 6 mg/L in aqueous solution, the electrochemical potential at the steel surface changes from positive to negative and depassivation of the underlying reinforcement takes place.

Mehta and Monteiro (1993) reported that if the molar ratio of the percentage of free chloride ions to percentage of hydroxyl ions (OH^-) is greater than 0.6, the passive layer will be disrupted despite the pH being above 11.5.

After depassivation, chloride ions can cause serious pitting corrosion by permitting the dissolution of steel reinforcement over a small area. Chloride ions also act as a catalyst to speed up the process of dissolution of iron in the anodic areas.

In addition, Bouwer (1998) reported that a large amount of chloride ions can lower the electrical resistivity of the concrete, since chloride ions themselves are mobile and permit the passage of current. They also have a tendency to attract more moisture, thus increasing the moisture content, resulting in a better conducting medium for easier movement of Fe^{2+} and OH^-.

2.3.4 Temperature

When the temperature is higher, chemical reactions generally become faster. These chemical reactions include carbonation, the diffusion of chloride ions and hence depassivation, as well as corrosion of steel reinforcement.

On the other hand, BRE Digest (1982) stated that a significant rate of corrosion would not occur generally below the temperature of about 10°C.

2.3.5 External Cracks on Concrete Surface

The presence of cracks on the concrete surface can provide pathways for the corrosion-inducing agents to reach the reinforcement, particularly when these external cracks are interlinked with the internal micro cracks in the cement paste.

Cracks formed transverse and parallel to the reinforcement have different effects. Cracks transverse to the reinforcement do not affect the corrosion of reinforcement as seriously (Beeby (1980) & Mehta and Gerwick (1982)). This is because they do not increase the cathodic areas for corrosion. They only allow, for example, more chlorides to penetrate and initiate the corrosion.

Cracks formed parallel to and along the reinforcement have the greatest effect on corrosion. They enlarge the depassivation areas and cathodic areas which favour the corrosion process.

2.3.6 Availability of Oxygen and Moisture

Oxygen is required in the cathodic reaction in the corrosion process, while moisture is required to provide an electrolytic link for the movement of ions. If either one of these two elements is missing, no corrosion can take place.

2.3.6 (a) Oxygen supply

The oxygen supply to the embedded steel reinforcement depends on the quality of the concrete cover. A high quality of concrete cover with low permeability can inhibit the diffusion of oxygen, and therefore, also the corrosion of reinforcement.

2.3.6 (b) Moisture within concrete pores

If the pores are permanently saturated, corrosion of reinforcement may not occur because diffusion of oxygen will be very slow. This is the reason why submerged concrete elements are not prone to corrosion damage.

On the other hand, if the pores are too dry, corrosion of reinforcement may also not occur because there is no electrolytic link for the movement of ions involved in the corrosion process. Richardson (2002) illustrated that significant corrosion activity occurs at the relative humidity of about 80%.

Figure 2.5 (Schiessl and Raupach (1990)) shows the relationship of oxygen and moisture and the rate of corrosion obtained by a special test on a specimen with a corrosion cell. The rate of corrosion in Figure 2.5 is measured by the electric current (macrocell-current) flowing between the anode and cathode, which is in proportion to the rate of metal removal by corrosion. The surface of the specimen was kept covered by water for 100 days so as to prevent air passage to the specimen. The macrocell-current first increased drastically as the application of water decreases the electrical resistivity. This high current remained for the first two weeks before a sharp drop due to the lack of oxygen supply at the cathode. Eventually, corrosion ceased about two months after water application. After the removal of the water cover on the 100^{th} day, the specimen was left to dry at relative humidity of 55%. The current increased again as there was oxygen supplied to the cathode. This test proves the influence of oxygen and moisture on the corrosion process.

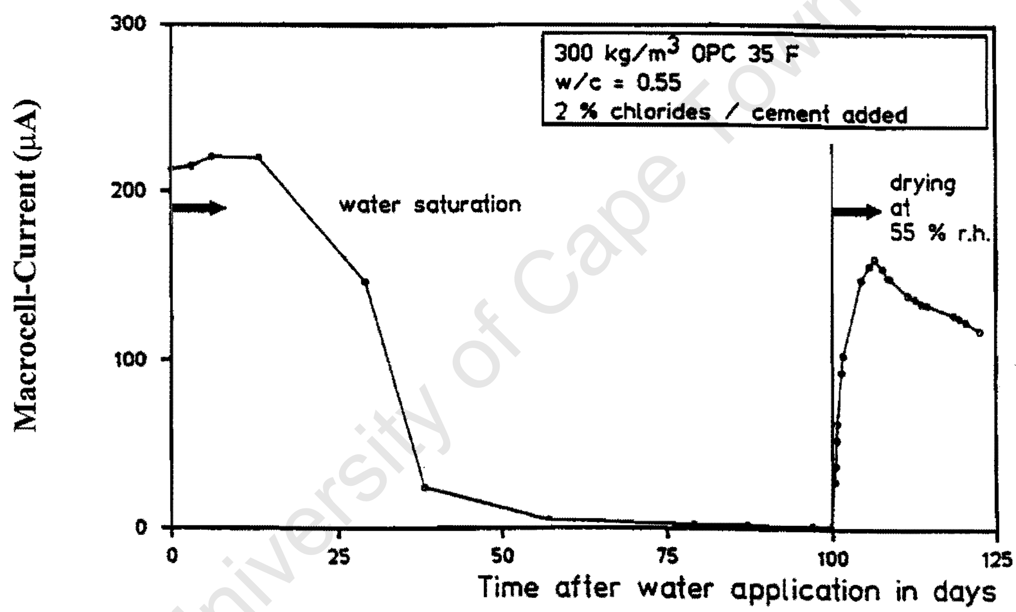


Figure 2.5: Influence of the water content of the concrete on the corrosion rate (Schiessl and Raupach (1990)).

2.4. CONSEQUENCES OF REINFORCEMENT CORROSION

The major consequences of reinforcement corrosion are cracking and spalling, as well as reduction of the load-carrying capacity of the structure.

The formation of one of the corrosion products, hydrated ferric oxide, causes an expansive force on concrete as its volume may be up to ten times the original volume of steel (Mackechnie and Alexander (2001)). Once this expansive force exceeds the tensile strength of the concrete, cracks develop. In some severe cases, spalling of the cover concrete results and this may lead to injuries. Figure 2.6 shows a reinforced concrete wing wall of a bridge with spalled cover, caused by reinforcement corrosion.

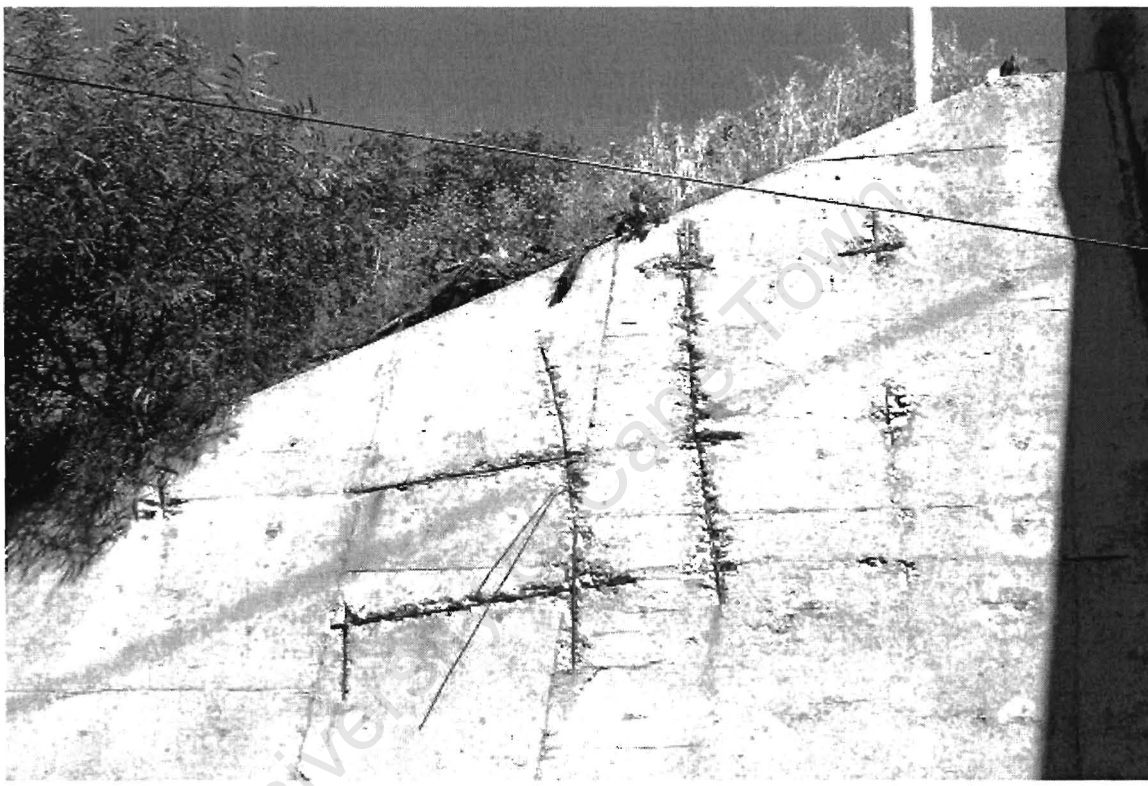


Figure 2.6: Spalling of concrete due to corrosion, bridge wing wall in Maitland, Cape Town.

In addition, the dissolution of the steel results in the reduction of the cross sectional area of the reinforcement. This leads to the decrease in load carrying capacity of the structure, especially in prestressed concrete structures.

These two major consequences of reinforcement corrosion always lead to high cost of repair. In some countries, the repair costs can reach as high as 3 to 5% of the Gross National Product (Broomfield (1997) and Yunovich and Thompson (2003)).

2.5. CONCLUDING SUMMARY

Corrosion of embedded reinforcement in concrete is an electrochemical process, in which the reinforcement acts as anode and also acts as an electric link to the cathode.

Corrosion of reinforcement occurs after depassivation. Depassivation results from a lowering of the alkalinity of the concrete due typically to the process of carbonation leading to the drop of pH of the pore solution, as well as the ingress of chloride ions. High temperature and sufficient supply of oxygen and moisture increase the rate and degree of corrosion.

As a consequence, corrosion of reinforcement causes problems of cracking and spalling of the cover concrete as well as decreasing the load-carrying capacity of the structure, leading to high cost of repair.

CHAPTER 3

CARBONATION OF CONCRETE

3.1 INTRODUCTION

In the previous chapter, a brief introduction to the causes and mechanism of the corrosion of steel reinforcement as well as its related consequences was provided. Carbonation is one of the causes leading to depassivation and hence corrosion of the reinforcement. In order to preclude damage in reinforced concrete structures due to carbonation-induced corrosion, a thorough understanding of the process of carbonation is necessary.

Carbonation refers to the action of carbon dioxide on a material. In terms of concrete, carbonation means the action of carbon dioxide on the hydration products of the binder. Carbon dioxide in the atmosphere diffuses into concrete from the surface through the concrete pores, and then reacts with the products of hydration. Through this reaction, the pH of the pore solution reduces and hence the concrete becomes less alkaline.

If the pH of the pore solution adjacent to embedded steel reinforcement is reduced due to carbonation, the protective passive layer formed on the surface of the steel reinforcement becomes unstable. Corrosion then occurs after the breakdown of this passive layer if both oxygen and moisture are present.

Richardson (2002) stated that carbonation itself seldom causes any structural problems, but carbonation-induced corrosion can cause aesthetic and/or structural problems such as cracking and spalling.

The present chapter highlights the mechanism and the factors which affect the rate of carbonation. It also provides and discusses prediction models for the depth of carbonation derived by different researchers.

3.2 MECHANISM OF CARBONATION OF CONCRETE

Carbon dioxide is a minor component of non-polluted atmosphere, being about 0.03% by volume. However, owing to this concentration difference between the atmosphere and the concrete pores, carbon dioxide diffuses through the surface of concrete and reacts with the hydration products of concrete resulting in the formation of different carbonate minerals.

3.2.1 Process of Carbonation

The process of carbonation can be divided into four stages.

Firstly, carbon dioxide in the gaseous phase diffuses into the concrete pores.

Secondly, there is the dissolution of solid calcium hydroxide in the presence of sufficient moisture:

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \qquad (3.1)$$

and the diffusion of dissolved calcium hydroxide in the pore water solution.

Thirdly, there is the dissolution of CO_2 in the pore water solution, which then reacts with the dissolved calcium hydroxide:

$$Ca^{2+} + 2OH^- + CO_2 \rightarrow CaCO_3 + H_2O \qquad (3.2)$$

Fourthly, carbon dioxide may react with calcium silicate hydrates and any unhydrated calcium silicates to form calcium carbonate and hydrated silica (Loo (1994) and Richardson (2002)):

$$3CaO.SiO_2 + 3CO_2 + xH_2O \rightarrow SiO_2.xH_2O + 3CaCO_3 \quad (3.3)$$

$$2CaO.SiO_2 + 2CO_2 + xH_2O \rightarrow SiO_2.xH_2O + 2CaCO_3 \quad (3.4)$$

In general, the far more important and significant reaction is the reaction of carbon dioxide with calcium hydroxide, and therefore carbonation of concrete can be simply represented by:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \quad (3.5)$$

3.2.2 Carbonation Front

Carbonation propagates as a front which separates carbonated and uncarbonated concrete (Addis (2001)). This front only moves beyond a certain point after the cement hydration products, mainly calcium hydroxide, as noted previously, have been converted into calcium carbonate at that point. Figure 3.1 (Rostam (1993)) shows the progress of the carbonation front through concrete.

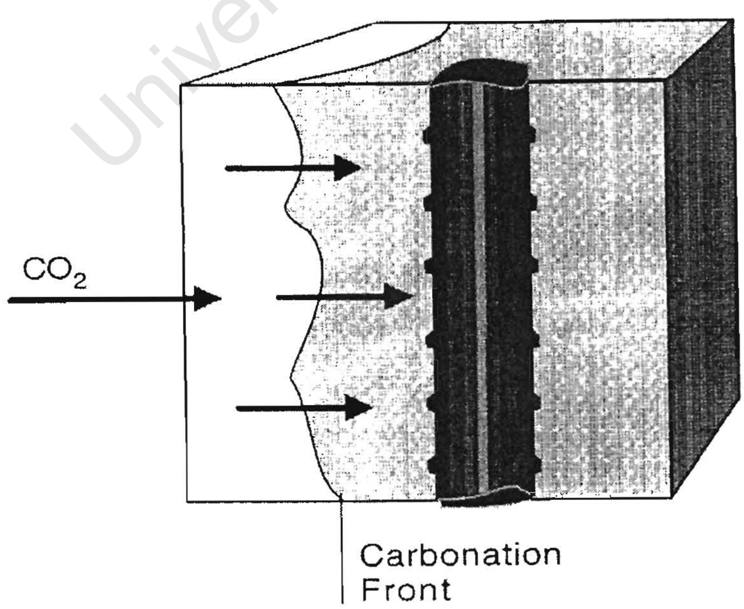


Figure 3.1: Progress of the carbonation front through concrete (Rostam (1993)).

In Figure 3.1, it should be noted that the carbonation front is not always a straight line owing to the presence of coarse aggregates (Neville (1995)) and material inhomogeneity; therefore part of the carbonation front can reach particular sections of the reinforcement and cause depassivation at those sections before others.

3.3 RATE OF CARBONATION

The rate of carbonation of concrete is primarily governed by two processes, namely diffusion of carbon dioxide and the formation of calcium carbonate. These two processes are influenced by the quality of concrete and environmental factors.

3.3.1 Processes That Govern the Rate of Carbonation

3.3.1 (a) Diffusion of carbon dioxide

The diffusion of carbon dioxide is initially driven by the concentration difference between the atmosphere and concrete pores. This results in a very thin layer of carbonated concrete of less than a millimetre (Richardson (2002)). Further diffusion depends on the permeability, relative humidity and temperature of the concrete.

3.3.1 (b) Formation of calcium carbonate ($CaCO_3$)

The formation of calcium carbonate requires chemical elements of carbon dioxide, oxygen and water. The ingress of these chemical elements again depends on the permeability and relative humidity of concrete.

In addition, calcium hydroxide which is one of the products of hydration, is also required in the formation of $CaCO_3$. The amount of calcium hydroxide depends mainly on the cement content and binder type, and will be explained in sections 3.3.2 (a) and (b) in more detail.

3.3.2 Factors Affecting Rate of Carbonation of Concrete

3.3.2 (a) Permeability

Permeability measures the ease with which an external agent can pass through the body of concrete under a pressure differential. Although permeation is not a process of carbonation, it is relevant insofar as it governs the rate or ease of ingress of carbon dioxide into concrete. The higher the permeability of concrete, the easier the diffusion of carbon dioxide into concrete, and the faster the rate of carbonation.

Permeability is a function of the pore structure (e.g. pore distribution, average pore size, pore connectivity) and microstructure (e.g. internal micro-cracking and interfacial transition zone) of concrete. A porous pore system can lead to a more permeable concrete as the likelihood of linking the pores (hence the formation of pathways) is increased, giving the phenomenon of percolation. Permeability is affected by water/cement ratio, curing and compaction.

- **Water/cement ratio**

In a concrete mix, the spaces originally occupied by mix water are called capillary pores. These capillary pores are filled by the products of hydration as cement hydration proceeds or they remain as open pores once the water which is not used by hydration, evaporates. This is illustrated in Figure 3.2.

Figure 3.2 shows that for a freshly mixed concrete, the unhydrated cement particles are initially surrounded by the mix water. As cement hydration proceeds, the hydration products are formed at the expense of the capillary pores which are originally occupied by the mix water. Further reduction of the volume of capillary pores results from further formation of hydration products as hydration proceeds. At long ages, a small volume of water-filled capillary pores remains. After the water in these capillary pores evaporates, an open pore structure will remain. The interconnection of these open pores will form a channel for species to ingress into the concrete. The higher the water/cement ratio, the larger will be the volume of water-filled capillary pore for species to transport through the concrete. Hence the concrete is more permeable.

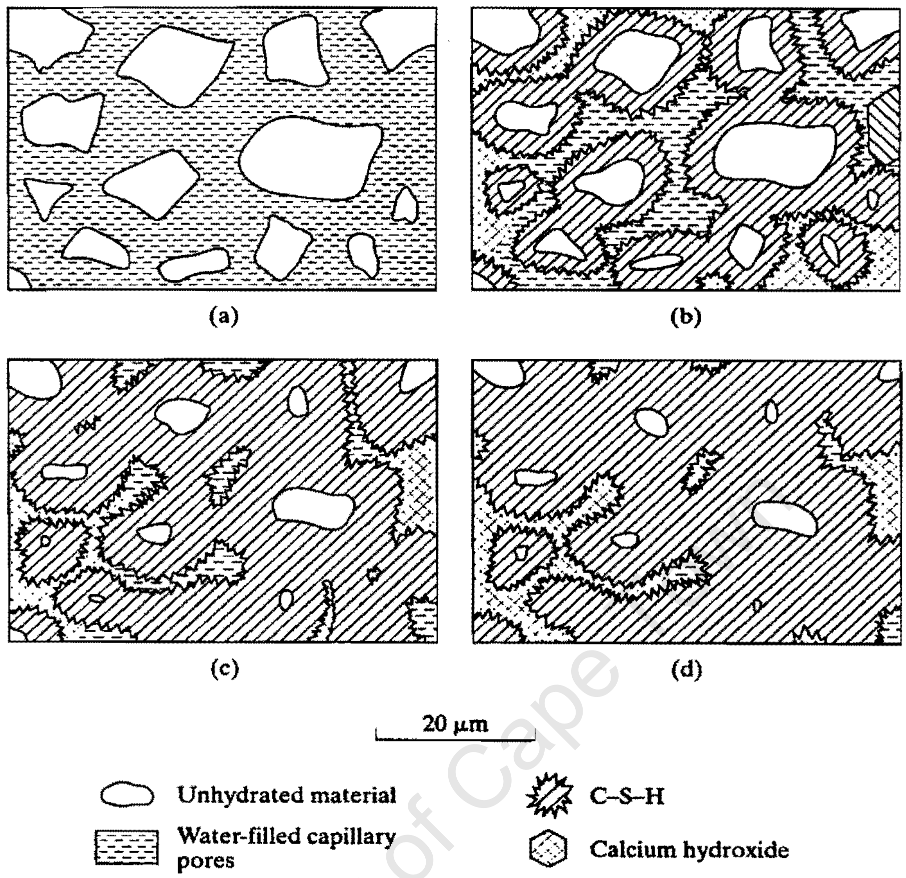


Figure 3.2: Schematic outline of microstructural development in Portland cement pastes: (a) initial mix; (b) 7 days; (c) 28 days. (Calcium sulfoaluminates are included as part of C-S-H for simplification, although they crystallize as separate phases.) (Mindess et al (2003)).

Referring to the limiting space criterion, the lower limit of water/cement ratio for full cement hydration is 0.38 (Neville (1995)). If the water/cement ratio increases above this lower limit, there is an excess amount of water present, leading to a greater amount of open capillary pores, resulting in higher porosity, as explained above.

It should be noted that high porosity does not always mean high permeability. Permeability depends on the degree of interconnection of, mainly, the capillary pores within the concrete. However, in general, assuming proper compaction and adequate curing, high water/cement ratio gives high porosity and yields higher permeability. This is illustrated by Addis (1994) as shown in Figure 3.3.

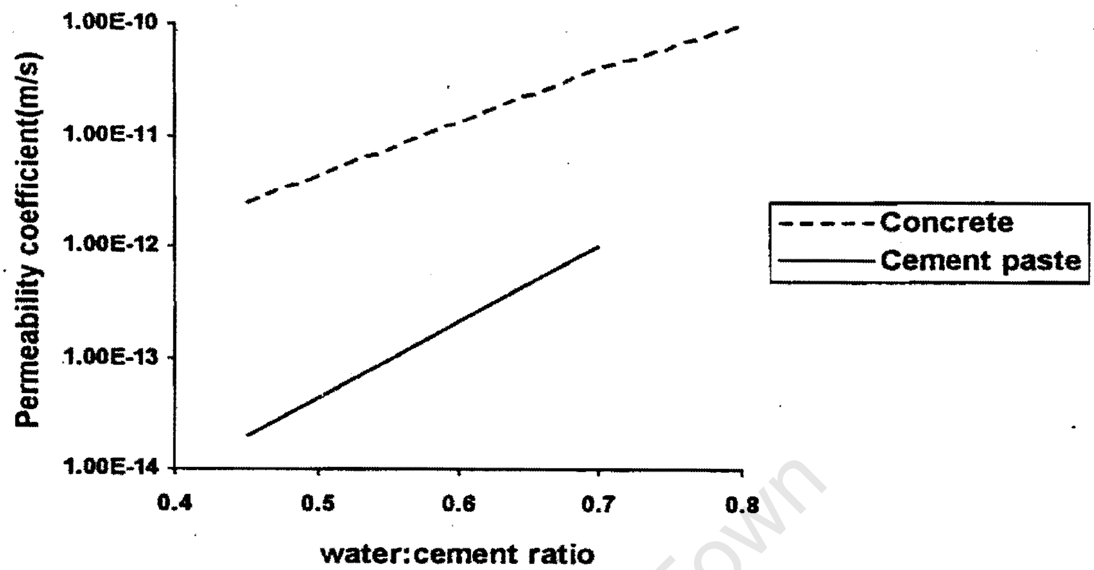


Figure 3.3: The influence of water/cement ratio on the permeability of cement paste and concrete (Addis (1994)).

The fact that high water/cement ratio generally yields high permeability of concrete and hence a high rate of carbonation is shown in Figure 3.4 (Meyer (1969)).

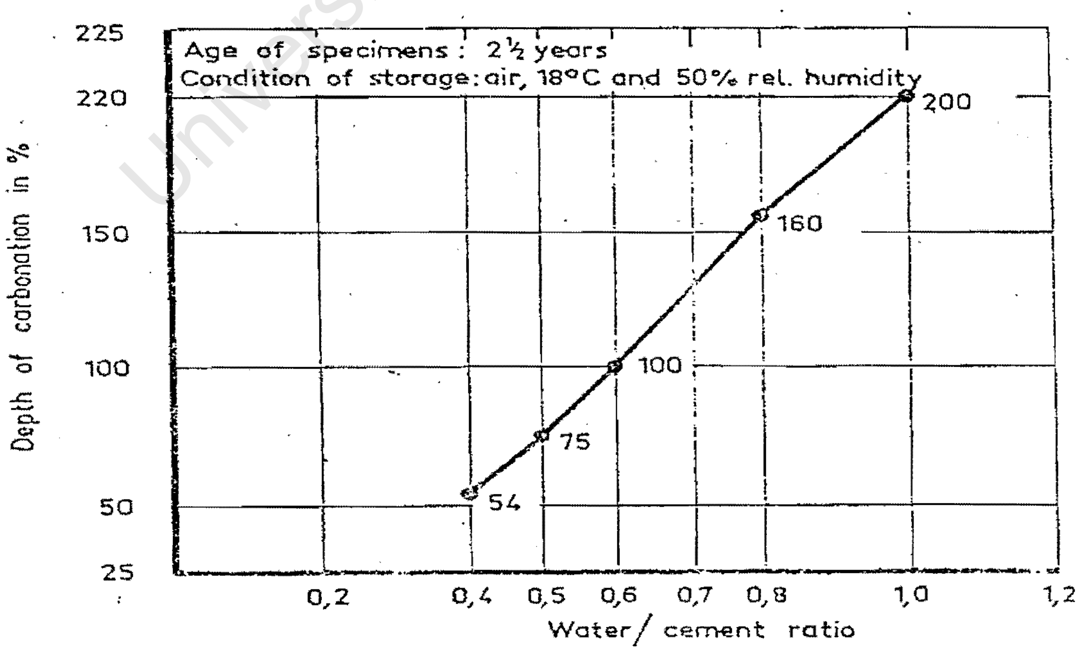


Figure 3.4: Effect of water/cement ratio on the rate of carbonation (Meyer 1969).

- **Curing**

Curing is the supply of moisture to the concrete in order to allow continuation of the cement hydration process. Bakker (1988) concluded that with sufficient moisture remaining in concrete at a constant temperature and composition, the permeability of concrete would decrease with increasing degree of hydration.

The products of hydration are formed during the cement hydration process, and are deposited in the capillary pores. As a result, the volume of the capillary pores is reduced, leading to a decrease in porosity. As stated above, low porosity generally indicates low permeability. A concrete with low permeability particularly in the cover concrete can greatly reduce the rate of carbonation.

However, cement hydration will cease if the capillary pores are in a state of insufficient moisture. This may happen when water evaporates to the surroundings. Once hydration is stopped, the reduction of volume of capillary pores becomes impossible as no further products of hydration occupy the pores. This leads to permeable porous concrete with a high rate of carbonation.

- **Compaction**

Besides gel pores and capillary pores, there exist air voids in the hardened cement paste within concrete. These air voids are of a greater diameter than gel pores and capillary pores. Thus, they can have a more significant effect on permeability, depending on their total volume and interconnectedness.

Air can be trapped within concrete during its fresh state. Through proper compaction, these air voids can be expelled and hence the quantity and size of the voids can be reduced. Hence, concrete becomes more impermeable and the rate of carbonation decreases with proper compaction.

3.3.2 (b) Type of Binder

Ordinary Portland cement (OPC) concretes are generally assumed to have a lower rate of carbonation than Pozzolanic (Fly Ash and Condensed Silica Fume) and Slag concretes, based on the argument that Pozzolanic and Slag concretes consume calcium hydroxide (carbonatable material) during the hydration process and hence reduce the amount of calcium hydroxide available for carbonation. This can speed up the process of carbonation and result in a higher rate of carbonation.

However, according to a report published by The Concrete Society (1991), for similar grade of concrete under similar curing conditions, carbonation appears to be unaffected at normal levels of Fly Ash and Slag. This conclusion was supported by Matthews (1984), and Thomas and Matthews (1992), who suggested that the normal levels of Fly Ash should be below 30% by mass of cement, whilst BRE (1992) showed that the cement replacement for Slag should be restricted to a maximum of 50% in order to limit carbonation.

3.3.2 (c) Cement Content

The amount of calcium hydroxide available for carbonation is directly proportional to the cement content. The higher the cement content, the larger the amount of calcium hydroxide produced under adequate curing conditions, and thus the longer the time required to neutralize the pore solution. As a result, the rate of carbonation generally decreases with increasing cement content.

Nixon (1986) stated that owing to the increase in the strength of cement in recent decades, the amount of cement used to manufacture a given grade of concrete has reduced. This implies that the water/cement ratio has also generally increased. The reduction of cement content has resulted in more permeable porous concrete, and therefore, rate of carbonation has increased.

3.3.2 (d) Atmospheric Carbon Dioxide Concentration

The penetration of carbon dioxide into the cover concrete is a diffusion process. Diffusion of carbon dioxide into concrete exposed to atmosphere is driven by the concentration difference between the atmosphere and the concrete pores in the cover zone. In normal atmospheres, the concentration of carbon dioxide is 0.03% by volume. Nischer (1986) reported that the concentration in tunnels and parking garages is about 0.3%, and Morinaga (1988) reported between 0.03% and 0.1% for well-ventilated buildings. The diffusion process and hence the rate of carbonation of concrete therefore increases with increasing carbon dioxide concentration of the atmosphere.

For illustration purposes, based on the United Kingdom and Ireland environments, Richardson (1988) reported that carbon dioxide concentration was found to be the lowest in coastal areas and highest in the internal environment such as the interior of buildings. As a result, the highest rate of carbonation also occurs in the internal environment. This higher rate of carbonation in internal environments is also probably due to the low relative humidity level, compared with other environments. Figure 3.5 shows the relative rate of carbonation in different environments (Richardson (1988)).

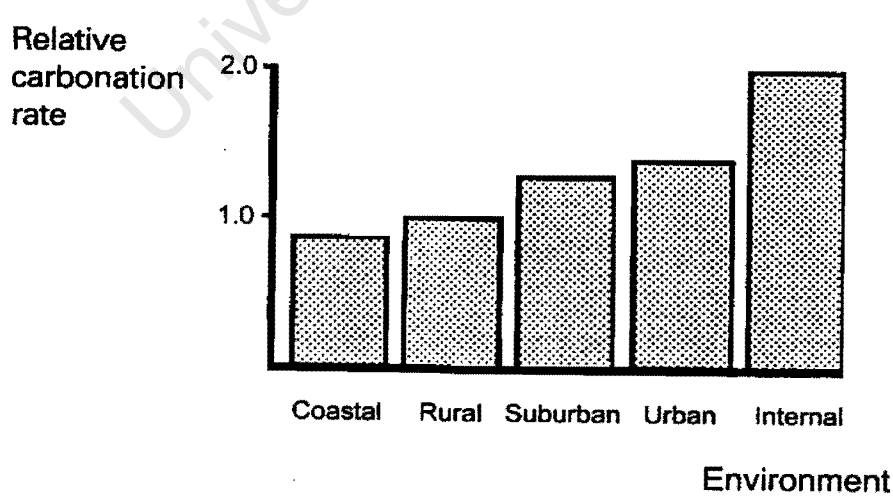


Figure 3.5: Influence of environment on the rate of carbonation, U.K. or Ireland environments (Richardson (1988)).

It should be noted that some regions (e.g. Johannesburg) in South Africa have drier environments than Richardson would have been referring to, and therefore carbonation outdoors can also be quite high.

3.3.2 (e) Climatic Conditions

Climatic conditions which can affect the rate of carbonation can be broadly divided into two aspects, namely, relative humidity and temperature.

- **Relative Humidity**

Carbonation is a diffusion process as mentioned before. Diffusion of carbon dioxide is very slow through water. ACI Committee 201 (2003) reported that if the concrete pores are relatively saturated in an area of high relative humidity (e.g. greater than 75%), rate of carbonation will be slow to negligible. On the contrary, a low relative humidity (e.g. less than 25%) also prohibits the process of carbonation due to insufficient water in the concrete pores for the dissolution of both gaseous carbon dioxide and calcium hydroxide.

The most favourable relative humidity for the process of carbonation and hence the fastest rate of carbonation should be in the range of 50% to 75% (ACI Committee 201 (2003)).

- **Temperature**

High temperature can accelerate the process and the rate of carbonation of concrete, as heat generally accelerates the majority of chemical reactions (Saetta et al (1993)). However, if concrete is subjected to high temperature over a prolonged period, the rate of carbonation becomes very slow. This is because most moisture in the concrete pores is evaporated. Owing to lack of moisture, carbonation cannot proceed or proceeds at a very slow rate (Saetta et al (1993)).

3.4 CARBONATION PREDICTION MODELS

There are several carbonation prediction models that exist in the literature. These prediction models are used to predict the depth of carbonation in the cover zone of concrete and hence give an estimate for the designer to provide an appropriate depth of the cover zone in order to avoid carbonation-induced corrosion.

These prediction models have been derived for various exposure conditions and for different parameters such as water/cement ratio. In other words, one particular prediction model may be appropriate only for the prediction of carbonation when the concrete has similar parameters and is subjected to the same exposure conditions as those for which the particular model was derived. Therefore, South African site data should be used to calibrate or validate the prediction models presented below.

3.4.1 General Prediction Model

It has been generally accepted that the depth of carbonation is proportional to the square root of exposure time (Addis (2001), Neville (1995), Richardson (2002) and Sarja and Vesikari (1996)). This relationship is based on Fick's first law of diffusion (Bakker (1988)) under ideal diffusion conditions (see below), and can be expressed as follows:

$$d_c = k\sqrt{t} \tag{3.6}$$

Where:

d_c = depth of carbonation (mm)

k = carbonation coefficient ($mm/\sqrt{years}$)

t = time (years)

The carbonation coefficient, k, depends on the:

- Permeability of concrete
- Type and content of binder

- Atmospheric carbon dioxide concentration
- Climatic and exposure conditions, such as temperature and relative humidity

The above prediction model applies to ideal diffusion conditions, which assume the cover concrete has a uniform pore structure and the concrete is exposed to a constant environment (Ballim and Lampacher (1996)). However, this square root relationship does not apply, for example, if the concrete is subjected to periodic wetting, since it is slower for carbon dioxide to diffuse through saturated pores (Neville (2003)). In this case, the exponent n in the general prediction model $d_c = kt^n$ could be expected to be less than 0.5.

3.4.2 Other Prediction Models

Richardson (2002) provides several prediction models which are available in the literature. These prediction models range from very complicated to apply, to very simple for practical uses. This thesis reports only the simple-to-use models selected from Richardson (2002), while others were selected from different researchers also based on simplicity. The models presented below, except for Ballim and Lampacher, Watkins and Jones, Parrott and Mackechnie, were selected from Richardson (2002).

(a)Uchida and Hamada (1928) proposed a prediction model with the inclusion of water/cement ratio to account for the permeability of concrete. The model is as follows:

$$d_c = \frac{(w/c) - 0.3}{\sqrt{0.3(1 + 3(w/c))}} (\sqrt{t}) \qquad (3.7)$$

Where:

d_c = depth of carbonation (mm)

w/c = water/cement ratio

t = time (years)

This prediction model does not allow for the climatic conditions, particularly the relative humidity of exposure. Therefore, a check for the validity of this prediction model against field data prior to the use of this model is necessary.

(b) Kishitani (1960) published two prediction models which differ for water/cement ratios below or equal to 0.6, and greater than 0.6. The models are as follows:

For water/cement ratio ≤ 0.6:

$$d_c = \frac{(4.6(w/c) - 1.76)}{7.2}\sqrt{t} \qquad (3.8)$$

For water/cement ratio > 0.6:

$$d_c = \frac{((w/c) - 0.25)}{\sqrt{0.3(1.15 + 0.3(w/c))}}\sqrt{t} \qquad (3.9)$$

Where:
d_c = depth of carbonation (mm)
w/c = water/cement ratio
t = time (years)

Again, these prediction models do not allow for the effects of the environmental conditions. Therefore, care should be taken when using these two prediction models.

(c) Alekseev and Rozental (1976) published a model with allowance for two specific water/cement ratios based on their research work. The model is shown below:

$$d_c = A(\sqrt[n]{t}) \qquad (3.10)$$

Where:
d_c = depth of carbonation (mm)

A = coefficient

n = 1.92 for water/cement ratio of 0.6

n = 2.54 for water/cement ratio of 0.7

t = time (years)

The coefficient, A, depends on climatic conditions as well as material factors such as binder type. The variable A may differ for different materials and exposure conditions, the value for this coefficient is not given here. In order to evaluate this coefficient for a particular area with concretes of these two particular water/cement ratios, sufficient field data from that area should be obtained.

(d) Ballim and Lampacher (1996) give a prediction model based on the climatic conditions in Johannesburg. Johannesburg has a mean carbon dioxide concentration of 0.035%, and mean relative humidity varies from a maximum of 79% in February to a minimum of 30% in dry winter season. The model is as below:

$$d_c = k\sqrt{t} \qquad (3.11)$$

Where:

d_c = depth of carbonation (mm)

k = carbonation coefficient

= an average of 3.76 mm/$\sqrt{\text{years}}$ under Johannesburg climatic conditions

t = time (years)

This prediction model was based on 45 core samples from 10 concrete bridges on the motorway system in Johannesburg. The binder type of these cores was presumed to be Ordinary Portland Cement. The elements from which the cores were taken were generally exposed to sun, wind and rain. The equivalent cube compressive strengths of these cores were assumed to be between 20 and 40 MPa based on historical records.

It should be noted that the average rate of carbonation is 3.76 mm/$\sqrt{\text{years}}$, whilst the maximum rate of carbonation found from these 45 cores is approximately 2.5 times this average rate. This indicates that their data show a wide scatter. This wide scatter is partly because they did not detect and hence eliminate any carbonation depth gross outliers, and partly because of the nature of the in-situ concrete.

(e) Watkins and Jones (1993) proposed a prediction model based on data from residential apartment blocks in Hong Kong. These apartment blocks were aged between 5 and 30 years. The climatic conditions of Hong Kong are quite similar to those of coastal regions of South Africa (Scott 1997), with mean relative humidity of 78% and average annual temperature of 23°C. However, the specimens that were studied were either sheltered or semi-sheltered such as those from balconies. The model was given as:

$$d_c = kt^x \qquad (3.12)$$

Where:

d_c = depth of carbonation (mm)

k = carbonation coefficient

t = time (years)

x = time exponent

Watkins and Jones (1993) studied a total of 14 132 samples in this investigation. These samples were then subdivided into three bands of concrete grade, namely, 15 – 24.9, 25 – 34.9 and 35 – 44.9 MPa. Power regression was then applied on these bands separately and yielded the results as shown in Table 3.1.

Table 3.1: Climatic conditions and values for Watkins and Jones (1993) Model.

Climatic Conditions	**Relative Humidity**	**Mean Annual Temp.**
	70% - 84%	23°C
Cement Type	Ordinary Portland Cement	
Grade of Concrete (MPa)	**k**	**x**
15 – 24.9	6.43	0.570
25 – 34.9	4.28	0.592
35 – 44.9	3.07	0.641

The time exponents x for their models range from 0.570 to 0.641, which are larger than the theoretical value of 0.5. This may due to: their prediction models were based on the early age sheltered or semi-sheltered elements, in which carbonation occurs most rapidly in the early age due to the pore structure improved with depth and time (see section 5.2.6 (a) for more detail), the methods of applying the power regression models (e.g. the assignment of the non-zero "initial" point, see section 5.2.6 (b) for more detail), and the conditions of the samples (presence of cracks).

(f) Parrott (1994) published a prediction model which included the parameters of air permeability of cover concrete, relative humidity and cement type with different calcium oxide content. The model is in the form:

$$d_c = [a\, k^{0.4}\, t^n] / c^{0.5} \qquad (3.13)$$

Where:

d_c = depth of carbonation (mm)

a = is a coefficient equal to 64 according to the published European data

k = air permeability of cover concrete which is highly dependent on relative humidity of cover concrete (in units of 10^{-16} m^2)

t = time (years)

n = exponential power to account for variation in the rate of carbonation owing to different relative humidities; n is given by:

$$n = 0.02536 + 0.01785r - 0.0001623r^2 \qquad (3.14)$$

(where r is relative humidity in %}

Typical n values for corresponding r-values are given in Table 3.2. This n value decreases with increasing relative humidity when the relative humidity is above 70%. This is because rate of carbonation decreases with increasing relative humidity.

Table 3.2: Values of n for corresponding r values (Parrott (1994))

r (%)	40	50	60	70	80	90	100
n	0.480	0.512	0.512	0.480	0.415	0.317	0.187

c = the calcium oxide content in the hydrated cement matrix which can slow down the rate of carbonation by reacting with carbon dioxide and expressed in kg/m^3 of cement matrix.

If the air permeability of cover concrete (k) is not known, it can be determined by drying the specimen at 60% relative humidity to obtain k_{60} (Parrott (1990)) and then using the equation:

$$k = m\, k_{60} \tag{3.15}$$

where: $m = 1.6 - 0.00115r - 0.0001475r^2$ (3.16)

or $m = 1.0$ if $r < 60$

Scott (1997) reported that if calcium oxide content is not given explicitly, it can be estimated by:

$$c = \frac{1000\rho_c}{\rho_c(w/c)+1}(cc) \tag{3.17}$$

where: ρ_c is the relative density of cement

w/c is the water/cement ratio

cc is the percentage of calcium oxide content of cement.

Equation 3.17 above assumes all calcium oxide will be available for conversion to calcium carbonate through carbonation.

Four assumptions were made in this prediction model. They are:

1. The air permeability of the cover concrete represents the diffusion coefficient of carbon dioxide
2. the carbon dioxide binding capacity is given by the amount of calcium oxide and the degree of cement hydration
3. the atmospheric concentration of carbon dioxide is constant
4. a deviation from the square root relationship between d_c and time, t, when subjected to wetter exposure given by simple diffusion theory

This prediction model allows for all major effects on the rate of carbonation, including the air permeability of cover concrete (diffusion of carbon dioxide), the relative humidity, binder type (in terms of calcium oxide content), and concrete quality (through the consideration of water/cement ratio), under the reasonable assumptions as listed above. However, sufficient South African data should be obtained in order to evaluate the suitable coefficient, a, in this prediction model prior to the application of this model for South African climatic conditions.

It should be noted that some of the prediction models presented above used a square root of time relationship and this is because of the application of Fick's first law of diffusion. However, this diffusion law is based on ideal diffusion conditions (Ballim and Lampacher (1996)). The diffusion of carbon dioxide through concrete is not under ideal conditions (such as pore structure is not uniform with time and depth) and therefore a deviation of such relationship results (Neville (2003)).

(g) Papadakis et al (1991) derived a prediction model to allow for non-ideal diffusion conditions. In other words, the diffusion of carbon dioxide into the concrete pores, the processes of carbonation described earlier, the reduction of porosity due to formation of products of carbonation, as well as relative humidity are all taken into consideration. A simplified version of this model is given by Papadakis et al (1992) and reported in Richardson (2002). The simplified model is as follows:

$$d_c = \sqrt{\frac{2[CO_2]D_{e,CO2}}{[Ca(OH)_2] + 3[CSH]}} \; (\sqrt{t}) \qquad (3.18)$$

Where:

d_c = depth of carbonation (mm)

$[CO_2]$ = molar concentration of carbon dioxide (mol/m^3)

$= 42\ y_{CO_2}$ where y_{CO_2} is ambient carbon dioxide content by volume

D_{e,CO_2} = effective diffusivity of carbon dioxide (m/s^2)

$$= (1.64 \times 10^{-6})\ \varepsilon_p^{\ 1.8}\ (1 - RH/100)^{2.2} \qquad (3.19)$$

$$\text{where } \varepsilon_p = (\rho_c/\rho_w)\ \{(w/c - 0.3) / [1 + (\rho_c/\rho_w)(w/c)]\} \qquad (3.20)$$

where ρ_c = mass density of cement (kg/m^3)

ρ_w = mass density of water (kg/m^3)

w/c = water/cement ratio

$[Ca(OH)_2]$ = molar concentration of carbon dioxide (mol/m^3)

$[CSH]$ = molar concentration of calcium silicate hydrate (mol/m^3)

And

$$[Ca(OH)_2] + 3[CSH] = 33\,000 / \{1 + (\rho_c/\rho_w)(w/c) + (\rho_c/\rho_a)(a/c)\} \qquad (3.21)$$

where ρ_a = mass density of aggregate (kg/m^3)

a/c = aggregate/cement ratio

It can be seen that this prediction model uses a square root relationship between the depth of carbonation and time. The square root of time ($\sqrt{t}$) was derived based on the numerical integration of the differential mass-balance equations for the diffusion, consumption and formation of carbon dioxide, calcium hydroxide, hydrated and unhydrated silicates, and therefore this square root relationship does not depend on the pore structure as well as climatic conditions. The pore structure and the climatic conditions are accounted for in the carbonation coefficient, as can be seen from equation 3.19.

This prediction model takes all reactions of carbonation of concrete into consideration. Therefore, this prediction model is complicated and requires quite a lot of information relating to the concrete mix, and thus, it may be useful for academic research but not particularly suitable for construction purpose.

(h) Mackechnie (1999) derived a prediction model based on laboratory specimens under climatic conditions of Cape Town. The specimens were 300 x 300 x 450 mm concrete blocks, placed outside the laboratory of the University of Cape Town for six years so that they were exposed to sun, rain and wind throughout the period. Cores were taken from the specimens after 1, 4 and 6 years to measure the depth of carbonation by spraying the cores with phenolphthalein solution.

Different binder types (Ordinary Portland Cement, Fly Ash and Slag) as well as different grades of concrete (20, 40 and 60 MPa) were investigated (see Table 6.2 in Chapter 6 for more detail). The prediction model is in the following form:

$$d_c = k_c t^x \qquad (3.22)$$

Where:
d_c = depth of carbonation (mm)
k_c = material coefficient (mm/year^x)
t = exposure time (years)
x = constant (varies between 0.1 and 0.4)

In this investigation, based on these types and grades of concrete, the power series constant x varied from 0.1 – 0.4. The values for k_c and x of all these concretes can be found in the spreadsheet (at UCT website (2000), http://www.civil.uct.ac.za/research/materials/concur.xls). Since the power constant, x is in the range of 0.1 to 0.4, a conservative value of 0.4 was selected by Mackechnie, as the power series constant for the Cape Peninsula climate. This conservative value is in good agreement with other research findings (Bentur and Jaegermann (1991) and Parrott (1995)). However, the collection of more field data is recommended in order to improve the material coefficients given in the spreadsheet as this investigation was only based upon one local climatic environment.

It should also be noted that the above prediction models may not always accurately predict the rate of carbonation particularly for in-situ concretes as high variability is shown by the in-situ carbonation data (see Ballim and Lampacher (1996) and Watkins and Jones (1993)). A discussion on the variability of the in-situ data is provided in section 5.7

Although so many prediction models are available, which model(s) is/are suitable for the three chosen South African localities (as far as this thesis is concerned) as they have different climatic conditions? This question will be evaluated by analysing the climatic conditions for these localities and field data which will be provided in Chapter 4 and 5.

3.4.3 Comparison of Carbonation Prediction Models in Literature

As a point of interest, the comparison of selected carbonation prediction models above can give an insight into the factors that govern the process of carbonation, such as binder type, constituent materials and exposure conditions. Models of Ballim and Lampacher (1996), Mackechnie (1999), Parrott (1994) and Watkins and Jones (1993) were selected owing to their simplicity for design and construction application.

The selected prediction models were evaluated by assessing a set of conditions typical of real concrete structures: assumed to be all ordinary Portland cement concretes with compressive strength of approximately 30 MPa, seven days moist curing, and exposed either to an average relative humidity of 60% or 80%. Figure 3.6

shows the predicted depths of carbonation against time of exposure for these models, under the above assumptions.

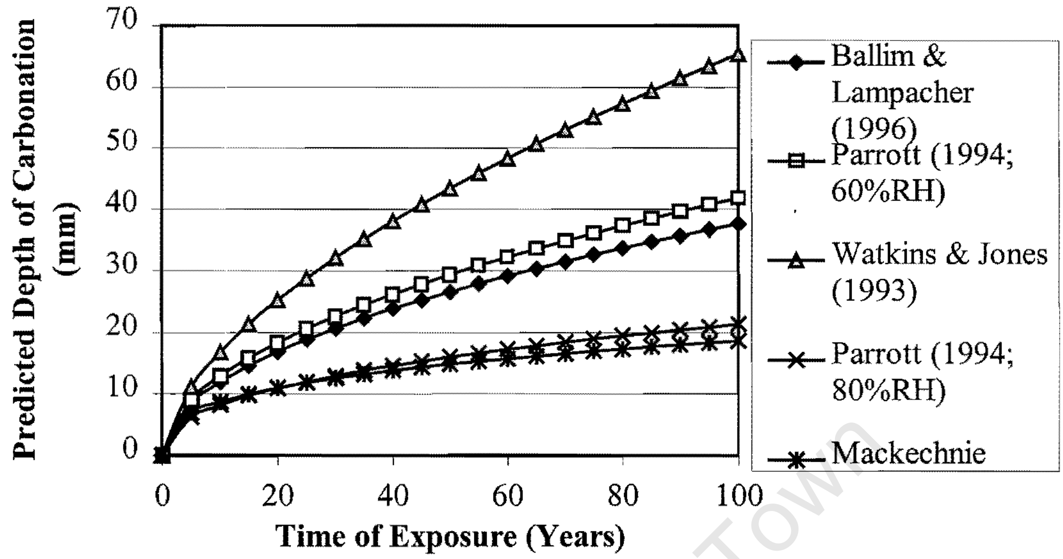


Figure 3.6: Comparison of selected carbonation prediction models in the literature

Watkins and Jones's (1993) prediction model has the highest depth of carbonation of all the models, whilst models of Ballim and Lampacher (1996) and Parrott (1994; 60%RH) agree with each other well, but differ significantly with models of Parrott (1994; 80%RH) and Mackechnie (1999).

Watkins and Jones (1993) prediction model was based on sheltered elements which were exposed to a relatively drier environment with relative humidity within the range of optimum relative humidity for carbonation of concrete, thus the predicted depths of carbonation should be the higher than the other prediction models which were based on exposed elements.

The models of Parrott (1994; 60%RH) and Ballim and Lampacher (1996) agree well with each other which can be attributed to the similar relative humidity of 60% that the concretes were exposed to. The depths of carbonation for these two models were higher than that predicted by Parrott (1994; 80%RH) and Mackechnie (1999). This difference is due to the fact that both models of Parrott (1994; 80%) and Mackechnie (1999) predict the depth of carbonation for concretes which are exposed to relative humidity of 80%. As noted previously, at 80% relative humidity, the rate of carbonation is slower than that at 60% relative humidity.

The comparison of these models stresses the importance of climatic conditions on the rate of carbonation and hence raises the point that a particular carbonation prediction model for a particular region (locality) is not applicable for other regions with different climatic conditions.

3.5 CONCLUDING SUMMARY

Carbonation of concrete can induce corrosion of the embedded steel reinforcement. This is because the conversion of calcium hydroxide to calcium carbonate can reduce the pH of the pore solution. The self-generated passive layer which can protect the reinforcing from corroding becomes unstable when the pH of the surrounding pore solution decreases to about 10.5. After the disruption of this passive layer, the steel reinforcement is vulnerable to corrosion if oxygen and moisture are present.

In order to avoid the corrosion of reinforcement and the concomitant consequences as described in Chapter 2 (section 2.4), rate of carbonation must be known. The rate of carbonation is controlled by both material and environmental factors. These factors are: permeability of cover concrete; type and content of binder; carbon dioxide concentration, exposure temperature and relative humidity.

Nine carbonation prediction models were given in this chapter. These models were derived under different exposure conditions and with different mix ingredients. A comparison was made between some of these models which are simple for practical use. It was found that these models predict similar carbonation depths with time, provided the binder type and exposure relative humidities are the same. Therefore, care should be taken when applying a particular prediction model to predict the depth of carbonation of concrete in that region.

As proved that climatic conditions have a major effect on the rate of carbonation, the study of the climatic conditions for Cape Peninsula, Durban and Johannesburg localities, for which carbonation of concrete is being investigated in this thesis, is necessary, and the important information in this regard will be provided in the following chapter.

CHAPTER 4

CLIMATIC CONDITIONS AND FIELD DATA OF CHOSEN LOCALITIES

4.1 INTRODUCTION

In the previous chapter, the importance of climatic conditions in relation to the rate of carbonation was discussed and it was shown that carbonation prediction models are sensitive to exposure conditions such as relative humidity. Therefore, it is necessary to have a knowledge of the climatic conditions of a locality for the derivation of a carbonation prediction model for that locality.

Climatic conditions can affect in-situ concrete structures in many ways including carbonation of concrete. Practically, the effects of climatic conditions on structures in terms of carbonation can be focused mainly on relative humidity.

Relative humidity is the ratio of the amount of water vapour in the air to the amount of water vapour that the air can hold at saturation at the same temperature (Hewitt (1989) and McBride (2001)). In other words, the relative humidity indicates how close the air is to saturation (McBride (2001)).

The most favourable relative humidity for the process of carbonation is between 50% and 75% (ACI Committee 201 (2003)). If a locality has a relative humidity within this range, carbonation of concrete can be pronounced.

In this chapter, the extent of each locality will be defined followed by the description of climatic conditions of three cities which represent the climatic conditions of the three chosen localities. These three representative cities are Cape Town, Durban and

Johannesburg. The carbonation data which were obtained from approximately 30 reinforced concrete bridges in each locality will be presented and hence a carbonation database for each locality is established. In the next chapter, the statistical analysis of the data and the carbonation prediction model for each of these localities will be derived based on these data.

4.2 EXTENT OF THE CHOSEN LOCALITIES

The general extent of the localities is given below. Detailed information including locality plans of the bridges on which carbonation data were measured in these localities will be given in section 4.4.

- Cape Peninsula locality refers to the central, northern and south-eastern parts of the Cape Peninsula.

- Durban locality: this covers the KwaZulu Natal south coast of Durban, Amanzimtoti, Illovo Beach, Umkomaas, Scottburgh, Pennington, Mtwalume, Hibberdene, Umzumbe, Umtentweni and Port Shepstone.

- Johannesburg locality: the greater Johannesburg area as well as between Heidelberg Road and Geldenhuis interchange, on the N3 Freeway.

4.3 CLIMATIC CONDITIONS FOR THE CHOSEN LOCALITIES

The climatic conditions for the cities of Cape Town, Durban and Johannesburg can give a general idea on the climatic conditions for the Cape Peninsula, Durban and Johannesburg localities respectively. The following sub-sections are based on Schulze's (1974) findings, with supplementary climatic data for the period generally between 1960 and 2000.

4.3.1 Cape Town

Cape Town is a coastal city and has a Mediterranean climate (Schulze 1974), with cool, wet winters and warm, dry summers. Considerable rainfall occurs in winter from May to September whilst less rainfall occurs in summer. During maximum rainfall periods in winter, an average of 12 to 15 rain days occur in a month, with approximately 4 to 5 rain days in a dry summer's month.

Winds are often strong and may reach gale force (Schulze 1974). Winds in winter are mainly northwesterly, whilst southeasterly winds dominate in summer.

The average monthly relative humidities of Cape Town are in the range of 70% to 80% with an average annual relative humidity of 75%. The average monthly temperatures are in the range of 12.3°C to 21.1°C with an average annual temperature of 16.8°C. See Table 4.1 (South African Weather Service (2003)).

Table 4.1: Average monthly relative humidity (based on mean hourly values) and temperature (based on average daily values) for the period generally between 1960 and 2000) for Cape Town. (South African Weather Service (2003)).

Month	Relative Humidity (%)	Temperature (°C)
January	70	21.0
February	70	21.1
March	73	19.9
April	76	17.5
May	80	14.9
June	80	13.0
July	80	12.3
August	78	12.7
September	76	14.0
October	72	16.1
November	70	18.3
December	70	20.1
Annual	**75**	**16.8**

4.3.2 Durban

Durban is also a coastal city and has a warm to hot and humid subtropical climate (Schulze (1974)). Durban has about 120 to 140 rain days per year. Rainfall is mainly in summer from October to March. During the highest rainfall season, Durban has about 15 rain days per month and only about 3 to 4 rain days per month in winter. Most of the rainfall is in the form of instability showers, and sometimes, heavy showers in short periods of time during the year can also occur.

Winds are northeasterly and southwesterly in about equal proportions, and are very unlikely to reach gale force.

The average monthly relative humidities of Durban are in the range of 71% to 80% with an average annual relative humidity of 77%. The average monthly temperatures are in the range of 16.6°C to 24.7°C with an average annual temperature of 20.9°C. See Table 4.2 (South African Weather Service (2003)).

Table 4.2: Average monthly relative humidity (based on mean hourly values) and temperature (based on average daily values) for the period generally between 1960 and 2000) for Durban. (South African Weather Service (2003)).

Month	**Relative Humidity (%)**	**Temperature (°C)**
January	80	24.4
February	80	24.7
March	79	24.0
April	78	21.8
May	75	19.2
June	71	16.9
July	71	16.6
August	73	17.8
September	77	19.4
October	78	20.4
November	79	21.9
December	79	23.5
Annual	**77**	**20.9**

4.3.3 Johannesburg

Rainfall occurs mainly in summer from October to March, and is mainly in the form of showers and thunderstorms, of short duration. An average of about 75 to 100 thunderstorms occur per annum. Winters are dry and cold.

Winds are generally southwesterly and light, besides during the short period of thunderstorms.

The average monthly relative humidities of Johannesburg are in the range of 46% to 70% with an average annual relative humidity of 59%. The average monthly temperatures are in the range of 10.1°C to 20.0°C with an average annual temperature of 16.0°C. See Table 4.3 (South African Weather Service (2003)).

Table 4.3: Average monthly relative humidity (based on mean hourly values) and temperature (based on average daily values) for the period generally between 1960 and 2000) for Johannesburg. (South African Weather Service (2003)).

Month	Relative Humidity (%)	Temperature (°C)
January	69	20.0
February	70	19.7
March	68	18.6
April	64	15.7
May	56	12.9
June	52	10.1
July	49	10.3
August	46	12.7
September	46	16.1
October	57	17.5
November	66	18.3
December	68	19.4
Annual	**59**	**16.0**

4.3.4 Comparison of Climatic Conditions Between the Three Localities

Carbonation of concrete is a diffusion process and the rate of this process is highly controlled by the relative humidity of concrete (detailed information in this regard can be found in section 3.3.2 (e)). Although the internal relative humidity of concrete relates to the external relative humidity of the air, it does not vary as rapidly as the external relative humidity. In order to assess the rate of carbonation, the average of external relative humidity for the "wet" and "dry" seasons might be useful, where "wet" season refers to the period with high rainfall and "dry" season to period with low rainfall. Table 4.4 shows the average relative humidity for these seasons for the chosen localities. In addition, Table 4.4 also shows the average temperature for the "wet" and "dry" seasons, as temperature can also affect the rate of carbonation even though to a smaller extent.

From Table 4.4, the Cape Peninsula and Durban localities have an average seasonal relative humidity of 78% and 79% during the high rainfall season respectively. This suggests that these two localities have a low rate of carbonation during this "wet" season, as the concrete pores are too wet for rapid diffusion of carbon dioxide into concrete. However, it may be expected that the carbonation rate for Durban is faster than that of Cape Peninsula during this season as the temperature for the former is about 9°C higher than the latter. During low rainfall season, the average seasonal relative humidity for the Cape Peninsula is 71% and for Durban is 73%. This indicates that the rate of carbonation is faster than that in the high rainfall season. Owing to the similar relative humidity and temperature, these two localities can be expected to have a similar carbonation rate in this low rainfall season.

In contrast, the Johannesburg locality would have a high rate of carbonation in both high and low rainfall seasons, since the average seasonal relative humidities for both seasons (i.e. throughout the year) are in the range for the optimum relative humidity for carbonation of concrete. Thus, for the same concrete, the Johannesburg locality should have a higher rate of carbonation than the Cape Peninsula and Durban localities as significant rates of carbonation for these two localities mainly occur in the low rainfall season only.

Table 4.4: Average relative humidities and temperatures for high and low rainfall seasons for the three localities.

Locality		Cape Peninsula		Durban			Johannesburg		
Rainfall	Month	Ave. Monthly RH (%)	Ave RH %	Month	Ave. Monthly RH (%)	Ave RH (%)	Month	Ave. Monthly RH (%)	Ave RH (%)
High (Wet)	April	76	78 (14)	Oct.	78	79 (23)	Nov.	66	68 (19)
	May	80		Nov.	79		Dec.	68	
	June	80		Dec.	79		Jan.	69	
	July	80		Jan.	80		Feb.	70	
	Aug.	78		Feb.	80		March	68	
	Sept.	76		March	79		April	64	
	-	-		April	78		-	-	
Low (Dry)	Oct.	72	71 (19)	May	75	73 (18)	May	56	51 (13)
	Nov.	70		June	71		June	52	
	Dec.	70		July	71		July	49	
	Jan.	70		Aug.	73		Aug.	46	
	Feb.	70		Sept.	77		Sept.	46	
	March	73		-	-		Oct.	57	

Note: The values in parentheses are the average temperature (°C) for the "wet" and "dry" seasons

The other significance of Table 4.4 is that it shows the risk of corrosion of reinforcement after depassivation. Richardson (2002) illustrated that the optimum concrete relative humidity for corrosion is above 80%. Therefore, the Cape Peninsula and Durban localities will promote corrosion in the high rainfall seasons. This point should be noted as in these two localities, rapid carbonation occurs in the low rainfall season whilst corrosion occurs in the high rainfall season. Thus particular attention should be paid to the design and monitoring of the reinforced concrete structures in these two localities since carbonation-induced corrosion is likely to be a cause for deterioration. On the contrary, Johannesburg locality will not promote rapid corrosion as its average seasonal relative humidity is well below the critical corrosion relative humidity. Therefore, carbonation of concrete would be rapid but extensive corrosion would not take place (Ballim and Lampacher (1996)). However, if moisture from other external sources (e.g. leakage) penetrates into the structures after carbonation-induced depassivation, extensive corrosion could still take place.

4.4 CARBONATION FIELD DATA FROM CONCRETE BRIDGE STRUCTURES

From the above discussion, the reinforced concrete structures in the Cape Peninsula and Durban localities have a high risk of being damaged by carbonation-induced corrosion, hence knowledge of the rate of carbonation in these two localities is required in order to design and monitor structures to avoid carbonation-induced corrosion damage in their design life. In spite of the fact that extensive corrosion might not occur in the Johannesburg locality, aesthetical compromise of structures due to localised corrosion should also be avoided. Based on these facts, an understanding of the rate of carbonation is desired, based on data for the in-situ structures. This is because in-situ carbonation depth data can best reflect the effects of the material and environmental conditions on the structures in these localities. The carbonation data from each locality are presented in the following subsections. It should be noted that it was difficult to obtain in-situ carbonation data. Because of the importance of in-situ data, all the carbonation data should be documented properly. The carbonation data from in-situ bridges are presented below, and represent a layout for a carbonation database for bridges and other structures.

It should also be noted that the bridges that are under investigations were without any barrier coatings applied to them. Otherwise, the rate of carbonation will be affected.

4.4.1 Cape Peninsula

The carbonation data were obtained from 30 in-service bridges in the Cape Peninsula area (see Appendix A for the locality plans for these bridges). The ages of these bridges range from 6 years to 76 years. The obtained data consist of names and numbers of the bridges, ages of the structures, types of elements and the equivalent cube compressive strengths of the core samples at the time of measuring the depth of carbonation. The data are presented in **Table 4.5** below.

The types of elements include parapets, abutments, ear walls, beams, columns and sides of decks. Their positions in the bridges are also included. For example, Abutment (S) means the abutment at the south side of the bridge. This was very useful to identify which abutment was being sampled, and made it easier to decide whether that element was exposed to or sheltered from sun, rain and wind.

The "strength at Test" of the sample refers to the equivalent cube compressive strength at the age of measuring the depth of carbonation. All samples were in the form of cylindrical cores from the bridges. The cylinders were 68 mm diameter even though the standard size should be 100 mm. This diameter was chosen because some of the cores were also used for assessing the Oxygen Permeability Index, which required samples of 68 mm diameter. Figure 4.1 shows the section of core used for all tests. The testing of the compressive strength of the cores was according to BS 1881 Part 120:1983. The core strengths were then converted to the equivalent cube strengths according to BS 1881:1983.

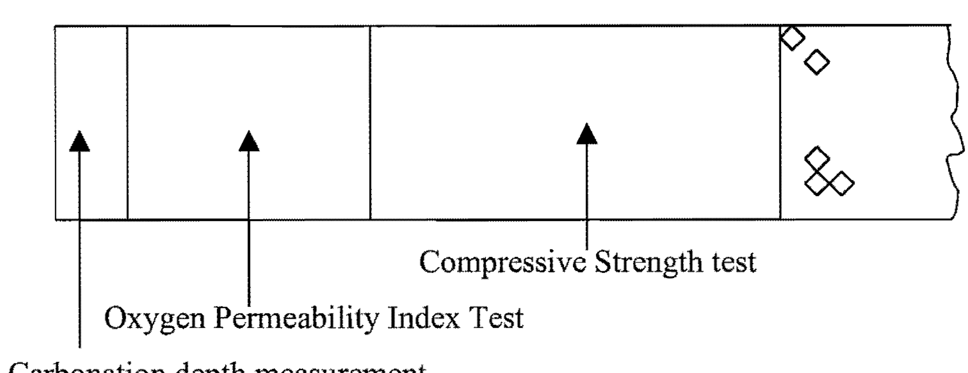


Figure 4.1: Section of core used for different tests in Cape Peninsula locality

The "Strength at 28 days" refers to the equivalent cube compressive strength of the sample at 28 days. The conversion from "Strength at Test" (later age strength) to "Strength at 28 days"(early age strength) for the sample will be provided in section 5.2.4.

However, not all compressive strengths of samples were tested. The blank entries (-) in Table 4.5 indicate that no compressive strengths were tested. The strengths at 28 days for those samples were assumed and are marked by an asterisk (*) in Table 4.5. This aspect will be explained in detail in section 5.2.4.

The depth of carbonation, d_c was measured by spraying phenolphthalein solution (1% by mass in ethanol/water solution) on the cores and then measuring the depth at eight equally spaced positions around the circumference of the core with a steel ruler. The reported d_c in Table 4.5 is the average of these 8 measurements.

The database will be elaborated in Chapter 5, by explaining how the compressive strength at the age of testing was converted to the approximate compressive strength at 28 days. The data will then be subdivided in terms of exposed or sheltered elements, the equivalent compressive strengths at 28 days, and the equivalent water/binder ratio.

Table 4.5: Carbonation database for Cape Peninsula locality

(Data provided by Ronne (2003))

Type of Bridge: Road-over-Road (Data provided by Ronne (2003))						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[B616/5597] Swartklip Interchange Ramp B (1990)	11	Parapet (W)	exposed	68.5	60	5
		Parapet (W)	exposed	-	60*	11
[B164/C5596] Frans Conradie (South) (1986)	15	Parapet (S)	exposed	59	49.4	7
		Parapet (N)	exposed	-	49.4*	7
[B168] Old Paarl Interchange (South) (1981)	20	Parapet (W)	exposed	-	44.4*	4
		Parapet (W)	exposed	54	44.4	5
		Ear Wall (W)	exposed	64.5	55.5	9
		Ear Wall (W)	exposed	-	55.5*	8
[B190] Bottelary Underpass (1979)	22	Parapet (E)	exposed	-	45*	8
		Parapet (E)	exposed	55	45	8
		Parapet (W)	exposed	-	41.6*	15
		Parapet (W)	exposed	52	41.6	18
[B724] Eersterivier Interchange (1968)	33	Parapet (E)	exposed	49.5	39.4	8
		Pier 1, Col. 1 (W)	exposed	42	32.2	10
		Pier 1, Col. 1 (W)	exposed	-	32.2*	18
		Pier 1, Col. 1 (E)	exposed	51	40.5	8
		Pier 1, Col. 1 (E)	exposed	-	40.5*	9
[B757] Macassar Beach (1968)	33	Parapet (W)	exposed	-	39.2*	5
		Parapet (W)	exposed	49	39.2	6
		Parapet (W)	exposed	-	39.2*	9
		Pier 1, Col. 1 (S)	exposed	-	27.7*	17
		Pier 1, Col. 1 (S)	exposed	36.5	27.7	10
		Pier 3, Col. 2 (N)	exposed	58.5	48.8	13
		Pier 3, Col. 2 (N)	exposed	-	48.8*	19

Table 4.5 (Cont')

Type of Bridge: Road-over-Rail (Data provided by Ronne (2003))						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[B320] Sarepta Road (1984)	17	Parapet (S)	exposed	56	46	8
		Parapet (S)	exposed	-	46*	7
		Ear Wall (S)	exposed	-	34*	4
		Ear Wall (S)	exposed	43.5	34	8
		Ear Wall (N)	exposed	-	43.8*	5
		Ear Wall (N)	exposed	53.5	43.8	4
		Pier 1, Col. 1 (N)	exposed	-	40*	4
		Pier 1, Col. 1 (N)	exposed	-	40*	4
Strength for the piers was based on common practice (Grade 30)						
[B589] Sir Lowry's Pass (1984)	17	Pier 46 (S)	exposed	53	43.3	9
		Pier 46 (S)	exposed	-	43.3*	10
[BE9128] Modderdam Road (1973)	28	Parapet (N)	exposed	69.2	60.5	8
[B758] Helderberg Road (1967)	34	Abutment (W)	exposed	46	36.1	9
		Abutment (W)	exposed	-	36.1*	10
		Abutment (E)	exposed	48	38.3	11
		Abutment (E)	exposed	-	38.3*	15
		Pier 1, Col. 1 (S)	exposed	-	35*	6
Strength for the pier was based on common practice & the measured strengths of other elements						
[BE6905] Victoria Road (1963)	40	Parapet (S)	exposed	-	40*	13
		Pier 1	sheltered	-	45*	20
		Pier 3	sheltered	55.3	45	23
Strength for parapet was assumed based on common practice and the measured strength for the piers						
[BE7125] Van der Stel (1961)	40	Parapet (W)	exposed	39.4	30	40
		Parapet (E)	exposed	-	30*	23
		Abutment (N)	exposed	46.9	36.9	16
[BE7090] Conradie Drive (1960)	41	Parapet (S)	exposed	51.4	41.6	7
		Pier 1	sheltered	-	35*	29
Strength for pier was assumed based on common practice (Grade 20-25) and the strength for parapet						
[BE6894A] Prestige Drive A (1959)	42	Parapet (E)	exposed	43.8	34.4	20
		Abutment (N)	exposed	31.1	23.1	27
		Pier 1	exposed	40.1	30.8	16
[BE6894B] Prestige Drive B (1959)	42	Wing Wall (SE)	exposed	-	30*	56
		Abutment (N)	exposed	38.7	30	26
Strength for wing wall was assumed based on common practice (Grade 20)						

Table 4.5 (Cont')

Type of Bridge: Road-over-Rail (Data provided by Ronne (2003)) (Cont')						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[BE6692] Halt Road (1958)	43	Parapet (E)	exposed	49.2	39.4	12
		Parapet (W)	exposed	-	39.4*	20
		Pier 3	sheltered	-	35*	21
Strength for pier was based on common practice (Grade 20-25) and strength for parapets						
[BE6526] De La Rey (1956)	45	Parapet (E)	exposed	48.3	38.3	6
		Parapet (W)	exposed	-	38.3*	17
[BE6705] Turfhall Road (1958)	45	Parapet (S)	exposed	34.4	26.1	25
		Abutment (W)	exposed	-	30*	8
		Pier 3	exposed	-	30*	7
Strength for the abutment & pier were assumed based on common practice (Grade 20) and strength for parapet						
[BE3558] Wetton Road (1956)	47	Return Wall	exposed	30.4	22.5	9
		Abutment (NW	exposed	-	30*	18
		Pier 4, Col. 1	sheltered	-	30*	42
		Pier 4, Col. 1	sheltered	-	30*	44
		Pier 4, Col. 1	exposed	-	30*	10
		Pier 13	exposed	-	30*	21
All the assumed strengths were based on common practice (Grade 20) and the strength for return wall						
[BE3392] Plumstead (1936)	67	Abutment (E)	exposed	39.8	31.1	11
		Pier 10	exposed	-	30*	19
		Pier 10	exposed	-	30*	22
Strengths for piers were assumed based on common practice and strength for abutment						
[BE7623] Woodstock Flyover (1964)	39	Abutment (S)	sheltered	-	47.5*	10
		Abutment (S)	sheltered	57.1	47.5	9
		Beam (N)	sheltered	-	41.6*	10
		Beam (s)	sheltered	51.8	41.6	8
[BE6317A] Maitland A (1961)	42	Abutment (W)	exposed	42.5	33.3	12
		Beam 1	sheltered	52.4	42.5	10
		Beam 2	sheltered	46.8	36.9	6
[BE6317B] Maitland B (1961)	42	Abutment (W)	exposed	-	33.3*	17
		End Block (NW)	exposed	46.8	36.9	7
		End Block (SW)	exposed	-	36.9*	11
Strength for the abutment was assumed according to the abutment of Maitland A						

Table 4.5 (Cont')

Type of Bridge: Road-over-River (Data provided by Ronne (2003))						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[B1494/5595] Stellenberg Ramp F (1985)	16	Parapet (S)	exposed	52.5	42.5	4
		Parapet (S)	exposed	41.5	32.2	7
[B630] Steenbras River (1976)	25	Ear Wall (S)	exposed	-	35.6*	4
		Ear Wall (S)	exposed	45.5	35.6	3
[B643] Palmiet River (1957)	44	Ear Wall (N)	exposed	-	30.8*	12
		Ear Wall (N)	exposed	40.5	30.8	13
Type of Bridge: Rail-over-River (Data provided by Ronne (2003))						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[BE8482] Elsies River (1969)	32	Deck Soffit	sheltered	-	30*	15
Strength for the deck was assumed based on common practice (Grade 20)						
[BE1624] Silvermine River (1926)	75	Side of Deck	exposed	-	30*	13
Strength for the deck was assumed based on common practice (Grade 20)						
[BE1582] Kalkbaai Viaduct (1926)	76	Pier 2	exposed	-	30*	12
Strength for the pier was assumed based on common practice (Grade 20)						
Type of Bridge: Footbridge-over-Road (Data provided by Ronne (2003))						
Bridge No., Name & Year of Construction	**Age (Years)**	**Type of Element**	**Exposure**	**Strength at Test (MPa)**	**Strength at 28d (MPa)**	**d_c (mm)**
[B1486] Khayelitsha Pedestrian (1995)	6	Abutment (S)	sheltered	56.5	47.2	9
		Abutment (S)	sheltered	-	47.2*	13

Age refers to the age at measurement of depth of carbonation
* means the assumed equivalent cube compressive strength of the core sample.
- means not measured, and a compressive strength at 28 days are assumed (see section 5.2.4)

Details for Common practice can be found in section 5.2.4

4.4.2 Durban Locality

A total of 32 bridges were studied in the Durban – (KZN) South Coast area. These bridges were located between Durban and Port Shepstone along the N2 freeway (location plan for these bridges are provided in Appendix A). Since Durban and Port Shepstone are relatively close, the data can be analysed together.

Data consist of the bridge numbers, names of the bridges, age and year of construction of the bridges, types of elements, design concrete strength grades and the depth of carbonation. Elements that were studied are deck soffits, abutments, columns, balustrades and wing walls. The data are presented in Table 4.6 below.

The ages of the bridges under investigation were between 17 and 45 years. It was assumed that all samples cored from deck soffits and abutments were sheltered from sun and rain and hence treated as sheltered elements. On the other hand, columns, balustrades and wing walls were regarded as exposed elements as they were generally exposed to sun, rain and wind.

The compressive strengths of the samples were not measured. However, most of the bridge drawings for these bridges are available, therefore the design concrete strength grade for most of the elements is known. Only some of the bridge drawings for bridges constructed between 1956 and 1964 are not available, an assumed concrete strength grade of 20 MPa was assumed (and marked by an asterisk (*)) based on the common practice for the bridges constructed in the same period.

The depths of carbonation were measured in-situ as follows (Moore (2003)): wedges were cut from the bridge element and phenolphthalein solution was sprayed into the opening after the removal of the wedge. The carbonation depth was measured using a steel ruler. One carbonation depth measurement was made for each opening. The d_c reported in Table 4.6 is the average value of these measurements. The number of measurement depends on the type of element as listed in Table 4.7.

Table 4.6: Carbonation database for Durban locality
(Data provided by Moore(2003)).

Type of Bridge: Road-over-Road (Between 1970 – 1982)						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B1238	Umgababa Station	1979	19	Deck Soffit	30	16
				Abutment	25	17
				Balustrade	25	27
				Wing Wall	25	18
B858	Isipingo	1982	21	Deck Soffit	30	18
				Abutment	25	21
				Column	30	10
				Balustrade	20	17
				Wing Wall	25	26
B163	Glendale Road	1977	24	Deck Soffit	25	18
				Abutment	25	24
				Balustrade	25	25
				Wing Wall	25	26
B209A	Wiggins Road	1976	25	Deck Soffit	25	24
				Abutment	25	19
				Balustrade	25	18
				Wing Wall	25	21
B209B	Wiggins Road	1976	25	Deck Soffit	25	22
				Abutment	25	28
				Balustrade	25	22
				Wing Wall	25	23
B37	Ridgeview	1976	25	Deck Soffit	40	7
				Abutment	30	11
				Column	40	3
				Balustrade	25	14
				Wing Wall	30	5
B114A	Edwin Swales (Main Road 82)	1976	25	Deck Soffit	40	18
				Abutment	25	21
				Column	30	12
				Balustrade	25	20
				Wing Wall	25	12
B114B	Edwin Swales (Main Road 82)	1976	25	Deck Soffit	40	15
				Abutment	25	24
				Column	30	13
				Balustrade	25	16
				Wing Wall	25	22

Table 4.6 (Cont')

Type of Bridge: Road-over-Road (Between 1970 – 1982) (Cont')						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B811	Kenyon Howden	1975	26	Deck Soffit	40	3
				Abutment	25	20
				Column	30	16
				Balustrade	25	16
				Wing Wall	25	12
B701	Higginson Highway	1973	28	Deck Soffit	40	7
				Abutment	25	13
				Column	30	21
				Balustrade	25	12
				Wing Wall	25	15
B810	Louis Botha	1976	28	Deck Soffit	30	15
				Abutment	30	17
				Column	30	18
				Balustrade	30	15
				Wing Wall	30	22
B854A	Winklespruit Interchange	1972	29	Deck Soffit	25	11
				Abutment	20	10
				Column	20	12
				Balustrade	25	11
				Wing Wall	20	12
B854B	Winklespruit Interchange	1972	29	Deck Soffit	25	12
				Abutment	20	15
				Column	20	23
				Balustrade	25	16
				Wing Wall	20	19

Table 4.6 (Cont')

Type of Bridge: Road-over-River (Between 1970 – 1982)						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B1233A	Mkomazi River	1982	17	Deck Soffit	45	11
				Abutment	30	7
				Column	35	12
				Balustrade	30	20
				Wing Wall	30	2
B1233B	Mkomazi River	1982	17	Deck Soffit	45	4
				Abutment	30	13
				Column	35	12
				Balustrade	30	14
				Wing Wall	30	7
B5A	Umlaas Canal (road and rail over canal)	1978	23	Deck Soffit	30	7
				Abutment	25	23
				Column	25	25
				Balustrade	25	22
				Wing Wall	25	23
B5B	Umlaas Canal (road and rail over canal)	1978	23	Deck Soffit	30	3
				Abutment	25	17
				Column	25	20
				Balustrade	25	15
				Wing Wall	25	24
B138A	Umhlatuzana Viaduct	1978	23	Deck Soffit	40	10
				Abutment	25	20
				Column	30	13
				Balustrade	25	19
				Wing Wall	25	22
B138B	Umhlatuzana Viaduct	1978	23	Deck Soffit	40	13
				Abutment	25	12
				Column	30	22
				Balustrade	25	24
				Wing Wall	25	18
B825A	Umzinto Valley Viaduct	1976	23	Deck Soffit	40	6
				Abutment	30	12
				Column	40	9
				Balustrade	25	8
				Wing Wall	30	14

Table 4.6 (Cont')

Type of Bridge: Road-over-River (Between 1970 – 1982) (Cont')						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B825B	Umzinto Valley Viaduct	1976	23	Deck Soffit	40	8
				Abutment	30	12
				Column	40	11
				Balustrade	25	10
				Wing Wall	30	2
Type of Bridge: Footbridge-over-Road (Between 1970 and 1982)						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B1170	World's View Footbridge	1975	24	Deck Soffit	25	21
				Abutment	25	5
				Column	25	9
				Balustrade	25	10
B1178	Isipingo Pedestrian	1970	30	Deck Soffit	25	8
				Abutment	25	19
				Column	30	10
				Balustrade	25	12
				Wing Wall	25	6
Type of Bridge: Road-over-Road (Between 1956 and 1964)						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B857	Dickens Road	1964	37	Deck Soffit	20*	18
				Column	20*	9
				Balustrade	20*	13
B1172	Umdoni Road	1964	38	Deck Soffit	20	12
				Abutment	20	14
				Column	20	18
				Balustrade	20	12
				Wing Wall	20	7
B856	Adams Road	1957	44	Deck Soffit	20	9
				Abutment	20	8
				Column	20	14
				Balustrade	20	20

Table 4.6 (Con't)

Type of Bridge: Road-over-River (Between 1956 and 1964)						
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Grade (MPa)**	**d_c (mm)**
B1177A	Isipingo River	1956	45	Deck Soffit	20	14
				Abutment	20	5
				Column	20	9
				Balustrade	20	14
				Wing Wall	20	8
B1177B	Isipingo River	1961	40	Deck Soffit	20	17
				Abutment	20	11
				Column	20	16
				Balustrade	20	20
				Wing Wall	20	16
B1176A	Umbogintwini River	1956	45	Deck Soffit	40	1
				Abutment	20*	11
				Column	20	0
				Deck Edge	40	24
				Wing Wall	20*	12
B1176B	Umbogintwini River	1956	45	Deck Soffit	40	0.4
				Abutment	20*	18
				Column	20	2
				Deck Edge	40	23
				Wing Wall	20*	10
B1179A	Isipingo Drainage Canal	1956	44	Deck Soffit	20*	17
				Abutment	20	24
				Column	20*	10
				Balustrade	20*	19
				Wing Wall	20	14
B1179B	Isipingo Drainage Canal	1956	44	Deck Soffit	20*	14
				Abutment	20	14
				Column	20*	12
				Balustrade	20*	15
				Wing Wall	20	21

* assumed value

It should be noted that, based on the bridge drawings, the design concrete strength grade for prestressed decks are mainly Grade 40, whilst normal reinforced decks are of lower grade.

Table 4.7: Number of measurements of carbonation depth for different types of elements for Durban locality (Moore (2003))

Type of Element	Number of Measurement
Deck Soffits	5
Abutments	2
Columns	2
Balustrades	4
Wing Walls	2

4.4.3 Johannesburg locality

The Johannesburg carbonation field data were obtained from bridges in the Johannesburg Motorway System as well as along the N3 between Heidelberg Road and Geldenhuis Interchanges. The data are presented in tabular form in Tables 4.8 and 4.9.

For the Johannesburg Motorway System field data (Table 4.8), "exposed" refers to samples exposed to sun, rain and wind; "sheltered" means samples sheltered from sun and rain whilst "weephole" indicates the samples sheltered from sun and rain but below weepholes. It should be noted that the "weephole" data are treated as exposed elements, although they were sheltered from direct rain, as they were wetted by rain water when the rain water drained from the weepholes.

All samples were extracted from columns of the bridges, and were 68 mm diameter cores. The cores were split and carbonation depths were measured by spraying 1% solution of phenolphthalein indicator in ethyl alcohol on the split surface. The reported d_c in Table 4.8 represent the average of three depth measurements. No compressive strength tests were done on these cores and therefore an attempt to evaluate the compressive strength will be given in section 5.4.4.

Table 4.8: Carbonation data of the Johannesburg Motorway System

(Data provided by Ballim and Lampacher (1996))

1. Motorway System of the Greater Johannesburg System (Ballim and Lampacher (1996))						
Type of Bridge: Road-over-Road						
Bridge Name	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
Harrow/Saratoga Bridge	1962	30	Column	exposed	20*	15
			Column	exposed	20*	34
			Column	exposed	20*	35
			Column	sheltered	20*	18
Goch St South Bridge	1965	27	Column	exposed	30*	14
			Column	exposed	30*	10
			Column	exposed	30*	18
			Column	exposed	30*	2
Goch St North Bridge	1966	26	Column	exposed	30*	20
			Column	exposed	30*	28
			Column	exposed	30*	14
			Column	exposed	30*	10
			Column	exposed	30*	16
			Column	exposed	30*	15
Empire Road Bridge	1968	24	Column	sheltered	30*	9
			Column	sheltered	30*	11
			Column	sheltered	30*	12
			Column	sheltered	30*	11
			Column	sheltered	30*	12
St Andrews Road Bridge	1968	24	Column	sheltered	30*	2
			Column	exposed	30*	15
			Column	exposed	30*	4
			Column	weephole	30*	3
Rissik St Off Ramp M2E Bridge	1968	24	Column	exposed	30*	20
			Column	exposed	30*	30
			Column	exposed	30*	41
			Column	exposed	30*	35
			Column	exposed	30*	20
			Column	exposed	30*	20
Loveday St M2 E/W Bridge	1968	24	Column	sheltered	30*	35
			Column	sheltered	30*	25
			Column	sheltered	30*	20
			Column	sheltered	30*	19

Table 4.8 (Cont')

1. Motorway System of the Greater Johannesburg System (Ballim and Lampacher (1996)) (Cont')						
Type of Bridge: Road-over-Road						
Bridge Name	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
1st Avenue Bridge	1971	21	Column	exposed	30*	13
			Column	sheltered	30*	17
			Column	sheltered	30*	20
			Column	exposed	30*	15
Corlett Drive Bridge	1972	20	Column	exposed	30*	8
			Column	exposed	30*	20
			Column	weephole	30*	24
			Column	weephole	30*	23
Booysens Road On/Off Ramp Bridge	1973	19	Column	exposed	30*	30
			Column	exposed	30*	19
			Column	exposed	30*	19
			Column	exposed	30*	17

* assumed value

For the data of Heidelberg Road and Geldenhuis Interchanges along N3 (Table 4.9), the depths of carbonation of different elements of the bridges were measured in the same way as in Durban locality. Elements include deck soffits, abutments, columns, parapets, wing walls and guard rails. Since the exposure conditions of the samples were not recorded, an assumption was made and verified in section 5.4.3. Also, the compressive strengths of the cores were not measured, and the assumptions were made based on the bridge drawings for the bridges in Durban locality (see section 5.4.4 for more detail).

Table 4.9: Carbonation Data of N3 between Heidelberg Road and Geldenhuis Interchange in Johannesburg locality (Data provided by Moore (2003)))

2. Along N3 Between Heidelberg Road and Geldenhuis Interchange (Moore (2003))							
Type of Bridge: Road-over-Road							
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
B216		1978	22	Deck Soffit	sheltered	35*	15
				Abutment	sheltered	30*	27
				Column	sheltered	30*	26
				Side of Deck	exposed	35*	23
				Wing Wall	exposed	25*	18
				Guard Rail	exposed	25*	19
B947	Elands System Interchange	1977	23	Deck Soffit	sheltered	35*	14
				Abutment	sheltered	30*	23
				Column	exposed	30*	23
				Wing Wall	exposed	25*	21
				Guard Rail	exposed	25*	7
B633	Elands Interchange	1977	23	Deck Soffit	sheltered	35*	16
				Abutment	sheltered	30*	23
				Column	exposed	30*	18
				Side of Deck	exposed	35*	17
				Guard Rail	exposed	25*	17
B634	Elands Interchange	1977	23	Deck Soffit	sheltered	35*	18
				Abutment	sheltered	30*	13
				Column	exposed	30*	18
B828A	Rand Airport Interchange	1977	23	Deck Soffit	sheltered	35*	9
				Abutment	sheltered	30*	17
				Column	exposed	30*	26
				Side of Deck	exposed	35*	23
				Wing Wall	exposed	25*	19
				Guard Rail	exposed	25*	21
B828B	Rand Airport Interchange	1977	23	Deck Soffit	sheltered	35*	8
				Abutment	sheltered	30*	18
				Column	exposed	30*	25
				Side of Deck	exposed	35*	10
				Guard Rail	exposed	25*	8
B828C	Rand Airport Interchange	1977	23	Deck Soffit	sheltered	35*	14
				Abutment	sheltered	30*	20
				Column	exposed	30*	24
				Side of Deck	exposed	35*	23
				Guard Rail	exposed	25*	21

Table 4.9 (Con't)

2. Along N3 Between Heidelberg Road and Geldenhuis Interchange (Moore (2003)) (Cont')							
Type of Bridge: Road-over-Road (Cont')							
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
B830	Radio Road Overpass	1977	23	Deck Soffit	sheltered	35*	15
				Abutment	sheltered	30*	21
				Column	exposed	30*	24
				Side of Deck	exposed	35*	11
				Wing Wall	exposed	25*	14
				Guard Rail	exposed	25*	11
B829	Radio Road Bridge	1977	23	Deck Soffit	sheltered	35*	16
				Abutment	sheltered	30*	24
				Side of Deck	exposed	35*	11
				Wing Wall	exposed	25*	18
				Guard Rail	exposed	25*	10
B831	Radio Road Bridge	1977	23	Deck Soffit	sheltered	35*	13
				Abutment	sheltered	30*	18
				Wing Wall	exposed	25*	18
B629A	Nortons Bridge	1977	23	Deck Soffit	sheltered	35*	23
				Abutment	sheltered	30*	18
				Column	sheltered	30*	21
B629B	Nortons Bridge	1977	23	Deck Soffit	sheltered	35*	21
				Abutment	sheltered	30*	18
B627	Access Road (Race Course) Bridge	1977	23	Deck Soffit	sheltered	35*	23
				Abutment	sheltered	30*	26
				Column	exposed	30*	22
				Wing Wall	exposed	25*	24
B212A	Access Road Bridge	1972	28	Deck Soffit	sheltered	35*	19
				Column	exposed	30*	30
				Side of Deck	exposed	35*	15
				Guard Rail	exposed	25*	16
B212B	Access Road Bridge	1972	28	Deck Soffit	sheltered	35*	20
				Column	exposed	30*	26
				Side of Deck	exposed	35*	17
				Guard Rail	exposed	25*	17

Table 4.9 (Con't)

2. Along N3 Between Heidelberg Road and Geldenhuis Interchange (Moore (2003)) (Cont')							
Type of Bridge: Road-over-Rail							
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
B546	Railway Bridge (Union Road)	1977	23	Deck Soffit	sheltered	35*	29
				Abutment	sheltered	30*	23
				Column	sheltered	30*	22
				Parapet	exposed	25*	15
				Wing Wall	exposed	25*	25
B26A	Railway Road Bridge (Natal Spruit Road)	1972	28	Deck Soffit	sheltered	35*	22
				Column	exposed	30*	31
				Side of Deck	exposed	35*	14
				Guard Rail	exposed	25*	14
B26B	Railway Road Bridge (Natal Spruit Road)	1972	28	Deck Soffit	sheltered	35*	24
				Column	exposed	30*	23
				Side of Deck	exposed	35*	12
				Guard Rail	exposed	25*	17

2. Along N3 Between Heidelberg Road and Geldenhuis Interchange (Moore (2003)) (Cont')							
Type of Bridge: Road-over-River							
Bridge No.	**Bridge Name**	**Year of Construction**	**Age (Years)**	**Type of Element**	**Exposure**	**Grade (MPa)**	**d_c (mm)**
B636A	Natal Spruit Stream Bridge	1977	23	Deck soffit	sheltered	35*	19
				Abutment	sheltered	30*	17
				Column	exposed	30*	11
B636B	Natal Spruit Stream Bridge	1977	23	Deck Soffit	sheltered	35*	22
				Abutment	sheltered	30*	14
				Column	sheltered	30*	13
				Wing Wall	exposed	25*	13

* assumed value

4.5 ASSESSMENT OF THE QUALITY OF THE DATA

4.5.1 Compressive Strength

In the Cape Peninsula locality, the majority of samples were tested for compressive strength. These later age compressive strengths were then converted to equivalent 100 mm cube compressive strengths at 28 days, and quoted in the Cape Peninsula locality carbonation database (Table 4.5). These strengths can be viewed as "true" strengths as no assumptions and estimation were made.

On the other hand, since there were no measurements of compressive strength for the samples of the Durban and Johannesburg localities, the "true" strengths for the samples are therefore unknown. The compressive strength is crucial in the study of carbonation of concrete as it can (roughly) reflect the concrete quality and hence give a better understanding of the carbonation data. Thus, for the data in the Durban locality, the bridge drawings were obtained and studied. These bridge drawings assisted in interpreting the quality of the bridge elements in this locality as they have the specified design concrete strength grades for the bridge elements.

Since there were no measurements of compressive strengths for the samples of the Johannesburg locality, and no bridge drawings were available, a reasonable approach has been used. That is to adopt the bridge practice of the bridges in the Durban locality, based on the grounds that the bridges constructed in these localities should have similar design strength grades (see section 5.4.4 for more detail).

Using the above approaches, a measure of concrete quality (based on the concrete strength) is known for the data in all three localities.

4.5.2 Depth of Carbonation

Neville (2003) pointed out that there is no ASTM or European standard for determining the depth of carbonation and this suggests that no single test procedure is as yet accepted. The test may be operator-sensitive. For example, the result would be different if one operator measures say, 3 points around the core while another operator measures 8 points of carbonation depth around the core.

It is generally accepted that carbonated concrete can be detected by the colour change of the concrete when sprayed with phenolphthalein solution. For carbonated concrete, there is no colour while there is a pink or purple colour for uncarbonated concrete. However, this indication may be misleading. Neville (2003) reported that phenolphthalein solution still remains pink when as much as 90% of the cement paste at the surface has been carbonated. This is because phenolphthalein solution shows pink when only a small quantity of alkali is detected. Nevertheless, the use of phenolphthalein solution is still the most common way in practice of measuring carbonation depth, owing to its simple to use and economic necessity.

Although the carbonation test may be regarded as operator-sensitive as well as the shortcomings of using phenolphthalein solution to detect the carbonated concrete zone as mentioned above, these data can still be accepted as they were generated by reputable operators or laboratories.

4.6 CONCLUDING SUMMARY

The general climatic conditions of Cape Peninsula, Durban and Johannesburg were given in this chapter. The rate and the depth of carbonation of concrete in Johannesburg locality are expected to be the highest in comparison with the other two localities. This is mainly because of its average relative humidities for both high and low rainfall seasons being in the optimum relative humidity range for carbonation of concrete. However, the problem of corrosion of reinforcement is not likely to be as serious as in the Cape Peninsula and Durban localities, because Johannesburg's relative humidity is too low to allow for significant general corrosion to take place. In contrast, the Cape Peninsula and Durban localities allow carbonation to proceed in the low rainfall season, whilst promoting corrosion of the reinforcement in the high rainfall season. Thus, carbonation-induced corrosion of reinforced concrete structures is very likely to take place in these two localities.

Carbonation data of many reinforced concrete bridges in these localities were collected from several sources, and a carbonation database was constructed for each of these localities. The data collected include the bridge numbers, age and year of construction of the bridges, the compressive strength of the bridge elements at the time of sampling (where available), type of element, the depth of carbonation and the physical location of the bridges.

In the next chapter, the data from these localities will be analysed separately after grouping them according to the concrete strength grades (quality) and exposure conditions, in order to derive the corresponding carbonation prediction models. The rate of carbonation for these localities will be compared, and the effects of climatic conditions on the carbonation rate will be discussed.

CHAPTER 5

CARBONATION PREDICTION MODELS FOR THE THREE LOCALITIES

5.1 INTRODUCTION

The differences in climatic conditions between the three localities, namely, the Cape Peninsula, Durban-South Coast and the Johannesburg area, and the effects due to these differences on the rate of carbonation of concrete, were highlighted in the previous chapter. In the present chapter, the carbonation data obtained from the bridges in these localities will be analysed separately.

Since limited information is available, this research focuses on two main factors which can influence the rate of carbonation of concrete. These two factors are exposure conditions and grade of concrete.

Exposure conditions of a concrete element affect the moisture state of the concrete. Moisture state of concrete pores has a marked effect on the diffusion of carbon dioxide into concrete as discussed in Chapter 3. Exposure conditions can be broadly divided into two categories, namely, exposed elements and sheltered elements. Exposed elements refer to elements which are exposed to direct sun, rain and wind, while sheltered elements would be sheltered from direct sun and rain. In other words, exposed elements generally have a higher moisture content than sheltered elements (depending also partly on the time of year or season).

Grade of concrete refers to the design or characteristic compressive strength of the concrete. Although the grade of concrete may not be a good indicator of the rate of carbonation, it is nevertheless a factor that concrete designers would commonly take into consideration when designing concrete structures for resisting applied loads and possibly where carbonation-induced corrosion is the main deterioration mechanism. Three grades of concrete were covered in the Cape Peninsula study whilst seven and five grade bands were studied in Durban Johannesburg localities respectively.

The carbonation data presented in Chapter 4 are grouped according to the factors mentioned above prior to statistical analysis. Two different methods of statistical analysis are used and will be presented in two parts. Part A uses the method of power regression using Excel and Part B applies the method of least squares to analysing the data. These two methods are employed and compared in order to select the most suitable carbonation prediction model for the three localities.

5.2 CAPE PENINSULA LOCALITY

5.2.1 Overview of Field Data

The detailed information on the carbonation data such as the age of each bridge, exposure conditions, types of elements, etc., was given in section 4.4.1. Figure 5.1 shows an overview of the data before grouping the data in terms of exposure conditions and grade of concrete. The carbonation data show a very wide scatter. This is not only because concrete itself is a variable material, but also because the data represent various conditions which can affect carbonation.

Figure 5.1 shows that the depth of carbonation increases from 6 to 47 years, with 4 data points which have carbonation depths of 40 mm or above. These 4 data points have marked high carbonation depths and may possibly be because of poor construction practice and the presence of cracks. A section discussing carbonation depth outliers will be provided in section 5.7 to discuss this issue in more detail. On the other hand, it is difficult to comment on the carbonation depths for the data aged between 67 and 76 years due to the limited number of data.

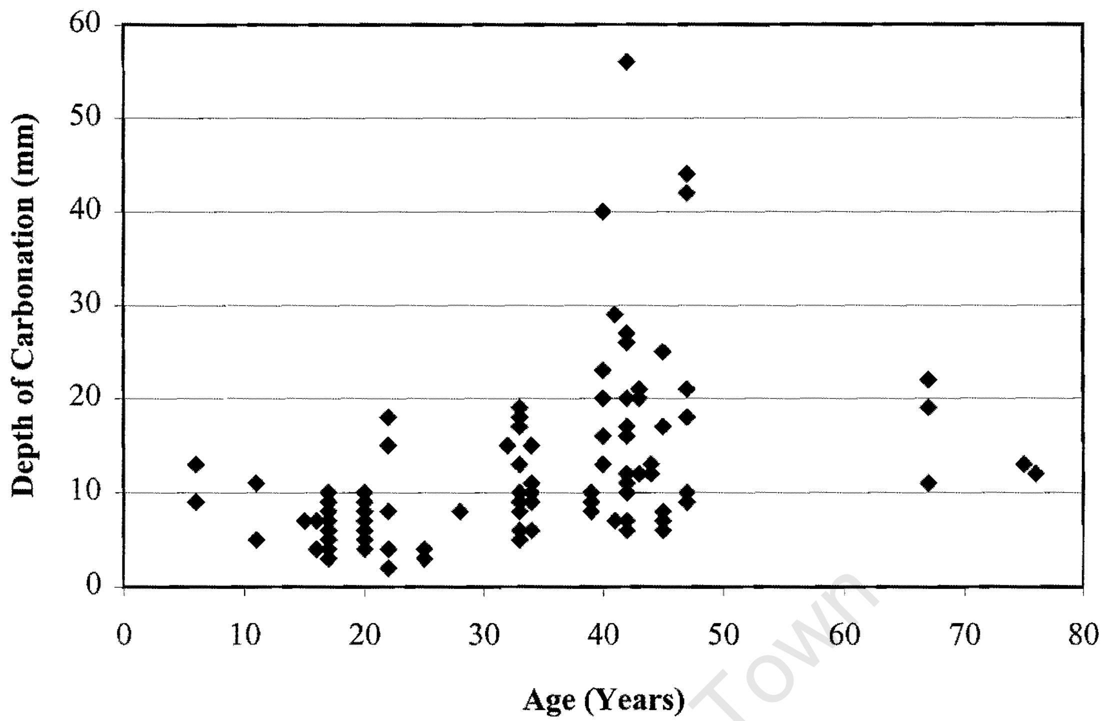


Figure 5.1: Overview of all carbonation data in the Cape Peninsula locality

5.2.2 Types of Bridges

The data derived from seven types of bridges, indicated in Table 4.5 of the previous chapter. They include road-over-road bridges, road-over-rail bridges, rail-over-rail bridges, road-over-river bridges, rail-over-river bridges and footbridge-over-road. The types of bridges may represent different environmental effects such as carbon dioxide level and moisture content. However, no reliable information in this regard was available.

Figure 5.2 and 5.4 show the depths of carbonation for all these types of bridges for the three selected 28 day compressive strength bands. The selection of these three strength bands will be explained in section 5.2.5 on the basis of the distribution of the number of data, whilst the inferred 28 days compressive strengths based on the later age measured compressive strengths will be provided in section 5.2.4.

Although some of the bridges are essentially marine structures and hence salt contamination may change the drying characteristics of their concrete surfaces (since salt is hydrophilic and holds on to moisture that would otherwise evaporate), it is not advisable to isolate any type of bridges from other types when analysing them. This is because their carbonation depths do not differ remarkably. Therefore, all types of bridges will be analysed together. If any data of any types of bridges differ significantly from the rest of the data, then they will be detected and eliminated by statistical means.

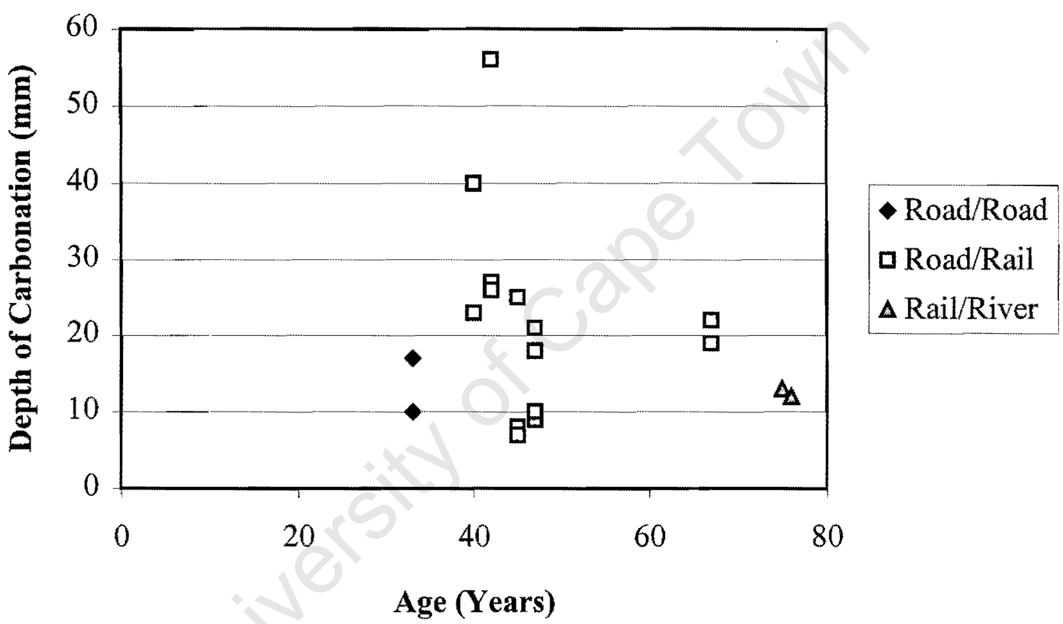


Figure 5.2: Carbonation depths for different types of bridges with compressive strengths between 21 and 30 MPa at 28 days

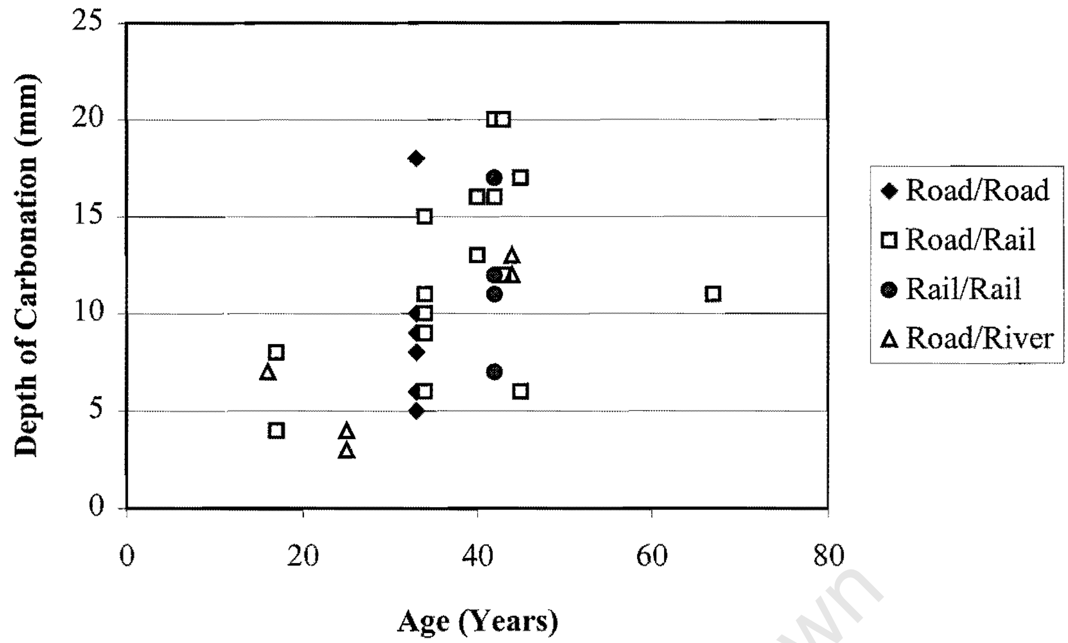


Figure 5.3: Carbonation depths for different types of bridges with compressive strengths between 31 and 40 MPa at 28 days

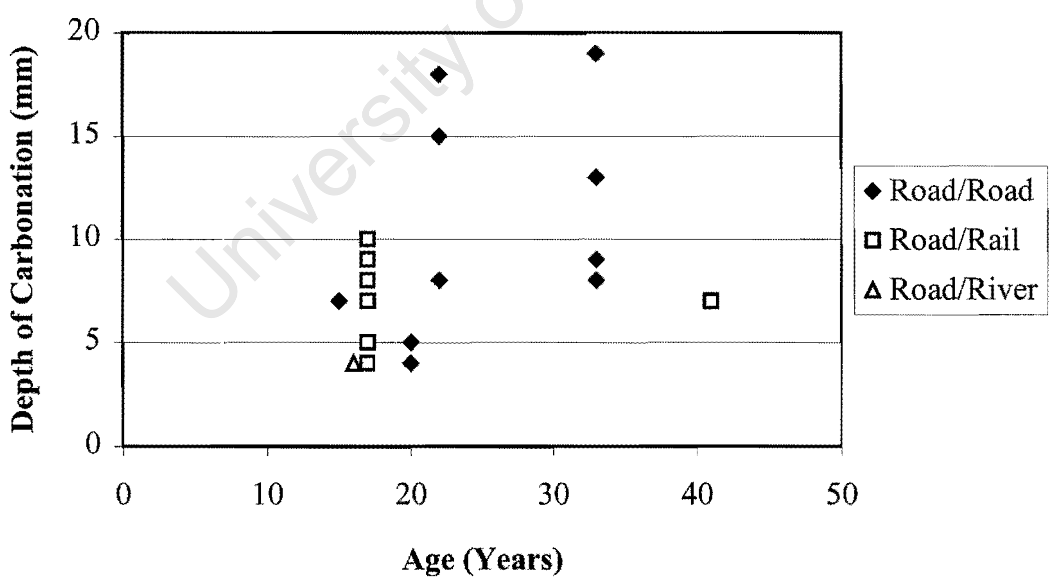


Figure 5.4: Carbonation depths for different types of bridges with compressive strengths between 41 and 50 MPa at 28 days

5.2.3 Determination of Exposure Conditions

Field trips to the bridges were arranged to examine whether the elements were exposed or sheltered from sun, rain and wind. Generally speaking, exposed elements included parapets, certain abutments (this depended on the position of the core), wing walls, ear walls and columns. Sheltered elements were abutments and deck soffits.

Exposed elements and sheltered elements were analysed separately as the rates of carbonation between them differ. Exposed elements are of particular interest as the corrosion of steel reinforcement occurs mainly in these elements due to their higher moisture content. In addition, the amount of data from sheltered elements is very small, and this can make the derivation of a carbonation prediction model difficult in terms of statistical analysis. Therefore carbonation prediction models are only derived for the exposed elements in the Cape Peninsula Locality.

5.2.4 Assessment of Equivalent Compressive Strength at 28 Days

The compressive strengths of the elements were obtained from drilled cores, and therefore represent later age strengths. Consequently, the compressive strengths of the elements are all at different ages. Due to the fact that concrete compressive strength changes with time, in order to make meaningful comparison between them, these strengths were standardised from the ages at testing to the age of 28 days. This was done by using the chart in Figure 5.5 published in Fulton (1977).

Figure 5.5 shows the relationship between compressive strength and cement/water ratio for ordinary Portland cement concretes. This specific graph is used because all the data were obtained from bridges which were made from ordinary Portland cement on the basis of the historic use of such cement in the Cape Peninsula at the time of construction of the bridges. Other binder types would need to use a different graph for that type of binder.

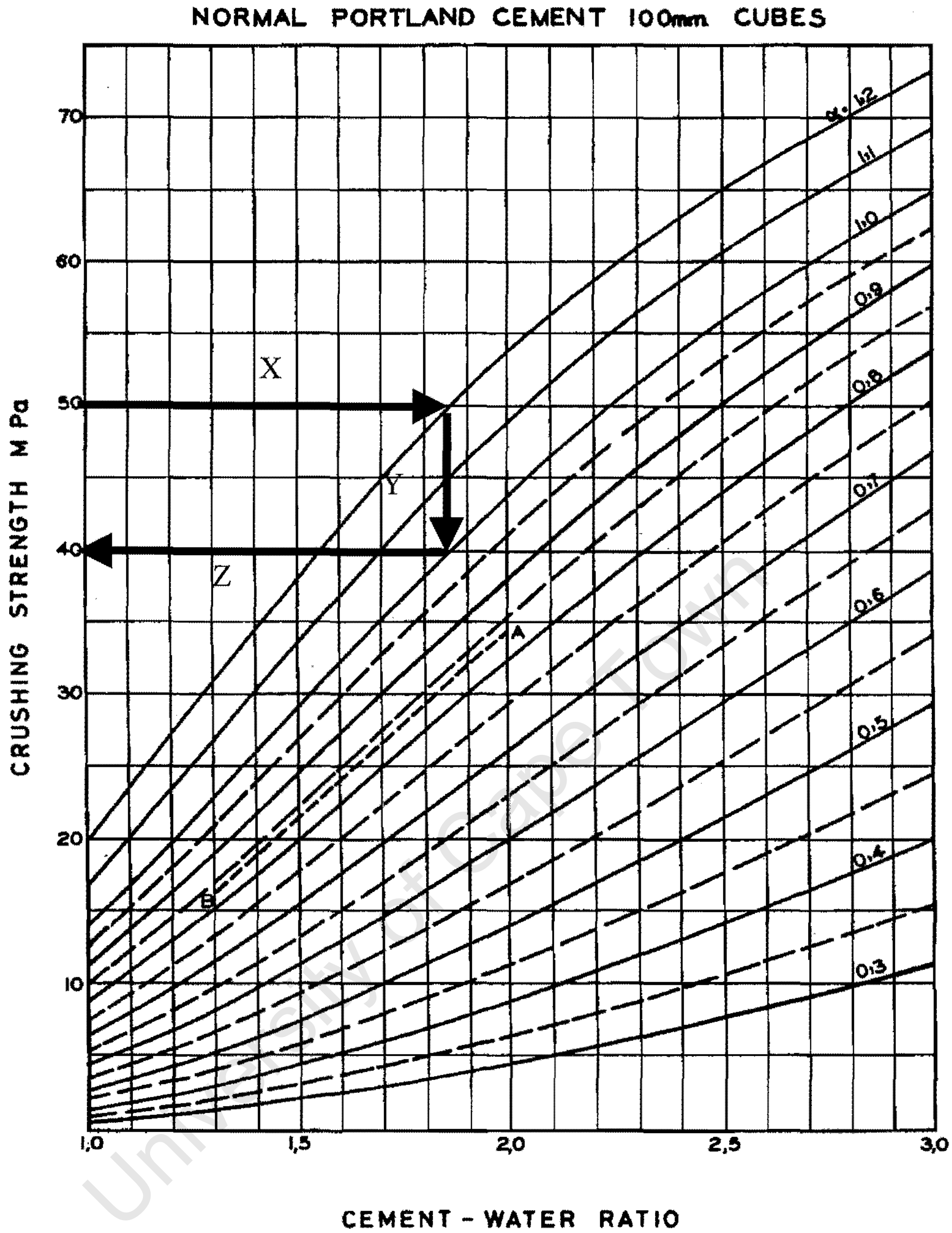


Figure 5.5: Relation between crushing strength and cement/water ratio of 100 mm ordinary Portland cement concrete cubes, with an example of XYZ (Fulton 1977).

In Figure 5.5, the vertical axis represents the crushing strength which is equivalent to the compressive strength of 100 mm cubes. The horizontal axis represents the cement/water ratio. The curves give the progress factor, α, which depends on the degree of cement hydration. For the mature concretes of the structures tested, it is assumed that an advanced degree of hydration has been achieved, represented by α = 1.2.

This chart is used as follows: take the compressive strength of the element at the age of testing and move horizontally to the curve of α = 1.2, then project vertically downwards to the curve of α = 1.0 which represents approximately the degree of hydration at 28 days, and then move horizontally leftwards to the vertical axis to read off the approximate compressive strength of the element at the age of 28 days. By way of illustration, an example is given on the figure marked as XYZ. X: represents equivalent long-term cube strength from the core strength measured (assumed as 50 MPa); Y: project vertically downwards from α = 1.2 to α = 1.0; Z: inferred cube compressive strength of concrete at the age of 28 days (40 MPa in this case).

As given in Table 4.5, there are a number of "-" entries for the 'Strength at test'. This means the compressive strengths for those cores were not measured at the time of measuring the depth of carbonation. The quality of concrete, and in particular the concrete grade as far as this research is concerned, has an important effect on the rate of carbonation as it can give a crude idea on the porosity and hence permeability of the concrete. Thus a compressive strength at 28 days for those cores should be assumed, based on realistic assumptions, in order that the carbonation data can be grouped accordingly for statistical analysis. Two such assumptions were made and the assumed strengths at 28 days are marked by an asterisk (*) in Table 4.5. If two or more cores were cut from the same element (such as abutment) of one bridge and compressive strength measurement carried out on only one of these cores, the other cores were assumed to have the same compressive strength as the measured one. On the other hand, if no compressive strength measurements were made on the cores from the same element of one bridge, then the compressive strengths were assumed based on common bridge design and construction practice and then compared with the measured strengths of other elements of that bridge in order to judge the validity of that assumed strength.

Common bridge practice informs the design grades specified for the elements of bridges in Durban locality. In addition, design grades for the same type of bridge element should be similar across the country when the bridges were constructed in the same period. Two construction periods are considered, namely, 1956 – 1964 and 1970 – 1982. These two construction periods are identified due to the change of the cement properties and this issue will be discussed in section 5.3.6.

The bridges constructed between 1950 and 1969 in the Cape Peninsula locality relate to 1956 – 1964 bridge construction practice of Durban locality, whilst bridges constructed from 1970 to 1984 are related to 1970 – 1982 bridge construction practice. It is important to mention that the specified design grade from common practice may not always reflect the actual compressive strengths as the actual in-situ strengths depend on many construction factors, for example, material batching, contractor's preferences, etc. Therefore, the assumed strengths which are based on common practice should be modified and then compared with the other elements of which compressive strengths were measured in order to test such modification. If this modification does not give a reasonable assumed strength, then further modifications may need to be made (see below).

It should be noted that the 28 day compressive strength is not the same as design grade. Grade (from common practice) refers to the specified compressive strength which represents a minimum strength such that 95% of the concrete should have a compressive strength higher than this specified strength. To ensure the concrete has a strength higher than the specified strength, the concrete strength would be targeted, depending on the variability of strengths, between 5 and 10 MPa higher than the specified strength. In this research, the carbonation data were obtained from field concretes. Assuming typical variations in strength of field concrete, the assumed target strength (strength at 28 days) is taken as about 10 MPa higher than the specified compressive strength (grade), i.e.

$$\text{assumed strength at 28 days} = \text{design grade} + 10 \text{ MPa}$$

If the assumed 28 day strength calculated according to the above formula differs substantially from the measured 28 day strength of other elements of the same bridge, then another modification to the assumed strength were made in such a way that the assumed strength does not deviate significantly from other measured strengths. Four bridges require the second modification and they are Helderberg Road, Victoria Road, Conradie Drive and Halt Road. According to the common practice in Durban locality, these three bridges were constructed in the 1956 – 1964 and therefore the elements of these bridges should be Grade 20 concretes which is equivalent to 30 MPa concretes in terms of strength at 28 days. However, the measured strengths of other elements of the respective bridges have much higher strengths, so the second modification was applied, on the grounds that the strengths for different elements of the same bridge constructed in that period were assumed not to be differed by too much.

5.2.5 Grouping of Concrete Grades

Owing to the small number of data from sheltered elements as mentioned before, only exposed elements were analysed for the Cape Peninsula bridges. All the exposed elements were subdivided into three groups of design strength grades according to the equivalent cube compressive strength at 28 days, estimated from their core compressive strengths at the age of testing based on the chart in Figure 5.5.

The grouping is based on the distribution of the exposed elements. Two possible grouping sets are shown in Figure 5.1. Grouping set 1 is better than Grouping set 2 because the distribution of elements in Grouping set 2 is not even, with two strength bands having 6 data points or less. A statistical analysis on a small number of data gives inaccuracy. Thus Grouping Set 1 was chosen for the analysis.

Grouping set 1 had four compressive strength bands: 21 - 30 MPa, 31 - 40 MPa, 41-50 MPa and 51 – 60 MPa at 28 days. Since the 51 – 60 strength band had only 4 data, therefore this strength band will not be analysed. The median compressive strengths for the strength bands that will be analysed in this locality are 25, 35 and 45 MPa.

Table 5.1: Distribution of exposed elements of bridges in the Cape Peninsula Locality

	Strength Band (MPa)	Median Strength (MPa)	Suggested Design Strength Grade (MPa)	No. of Data
Grouping Set 1	21 – 30	25	Grade 20	18
	31 – 40	35	Grade 30	33
	41 – 50	45	Grade 40	20
	51 - 60	55	Grade 50	4
Grouping Set 2	25 – 35	30	Grade 25	29
	36 – 45	40	Grade 35	18
	46 – 55	50	Grade 45	6
	56 - 65	60	Grade 55	3

It should be noted that median compressive strengths are not the same as design concrete strength grades as explained in section 5.2.4. The division of data for Durban and Johannesburg localities are however based on the design strength grade (since only the design strength grades for the samples are available), a conversion from the median compressive strength to design strength grade for the data in this locality is thus necessary for being consistent with the other two chosen localities. The suggested design strength grades for the compressive strength bands are shown in Table 5.1.

Hence, Grade 20, 30 and 40 exposed concrete elements of the Cape Peninsula locality will be analysed in the following sections.

5.2.6 Derivation of Carbonation Prediction Models

Chapter 2 of this thesis outlined the negative consequences of corrosion to reinforced concrete structures, and Chapter 3 explained that carbonation of concrete is one of the most common causes to initiate such corrosion. Also chapter 4 outlined that the climatic conditions of all three selected localities do favour carbonation of concrete to different degrees. Therefore, in order to avoid the damages caused by carbonation-induced corrosion to existing structures, a carbonation prediction model is required for the preparation of maintenance plans for existing reinforced concrete structures. Similar models are required for the design of new reinforced concrete structures, although changes in cement properties may make this task more difficult. Thus, in the present work, the models relate only to the types and ages of structures used in their derivation.

Chapter 3 pointed out that a carbonation prediction model is generally in the form of:

$$d_c = kt^n \qquad (5.1)$$

where d_c is the depth of carbonation in mm

k is the carbonation coefficient allowing for both material and environmental effects in mm/year^n

n is the power series constant, which should be close to 0.5

Chapter 4 highlighted the necessity of obtaining in-situ data in the derivation of a prediction model for each of these three localities. However, the in-situ data display a very wide scatter as shown previously in this chapter. This may require statistical approaches to reduce the scatter prior to the derivation of such models. Therefore, empirical models, based on site data, and statistically analysed for each of the localities, will be required, and are presented in the following sections.

Two statistical methods were used to analyse the field data and will be presented in two parts. Part A presents power regression using the spreadsheet programme Excel to fit a power trend line (in the form of equation 5.1) to the field data after the detection and elimination of gross outliers by means of residual analysis. As a further step in this method, early age laboratory data were then incorporated with the field data so as to reduce bias in the fitted power trend line. Part B presents the application of method of least squares to evaluate the best-fit power series constant, n to the field data.

PART A: POWER REGRESSION
(USING EXCEL SPREADSHEET)

The statistical method of power regression using Excel Spreadsheet was used to analyse the data of the Cape Peninsula locality only as this thesis will show that this common method is not suitable for the derivation of prediction model based only on later age data. Since the obtained data in all three localities are mainly later age, thus the application of this method in the following section is mainly for demonstration purposes. Through the demonstration of using this method, several important issues relating to carbonation predictions are discussed and hence caution should be taken.

(a) Power Regression Analysis of Field Data

This method involves performing a power regression analysis of the field data by using an Excel Spreadsheet. The Spreadsheet fits a power regression model to the data which indicates the trend of the rate of carbonation. This fitted model can then be used to detect any carbonation depth gross outliers which exist in the data set by means of examining the difference between the fitted value given by the fitted model and the field data. After the elimination of all gross outliers, a prediction model is obtained.

A detailed analysis of grade 20 exposed concrete is shown below as an example to illustrate the application of this method, whilst the same analyses of grade 30 and 40 exposed elements are given in Appendix B.

• Grade 20 (Exposed elements)

Grade 20 is taken as the nominal grade of field concretes which have compressive strengths between 21 and 30 MPa at 28 days. For this grade of concrete, nine bridges with a total of 18 carbonation results were analysed. The detailed information of these bridges was given in Table 4.5.

By plotting the graph of depth of carbonation against age of bridges on the Excel Spreadsheet, the spreadsheet can fit a trend line as well as give the coefficient of correlation, R^2, which is used for the purpose of judging how well the trend line is fitted to the data set. It should be noted that a non-zero "initial" data point is required in order to fit such a trend line. This is because the Excel Spreadsheet transforms the non-linear power regression model to a linear logarithmic model to perform such analysis. Therefore, an "initial" point of 0.1 mm depth of carbonation at the age of 0.01 years was assigned. A closer examination of this non-zero "initial" point will be discussed in section 5.2.6 (b).

Figure 5.6 below shows the fitted model to the data set before the detection and elimination of gross outliers. The fitted model is:

$$d_c = 1.732t^{0.595} \quad (5.2)$$

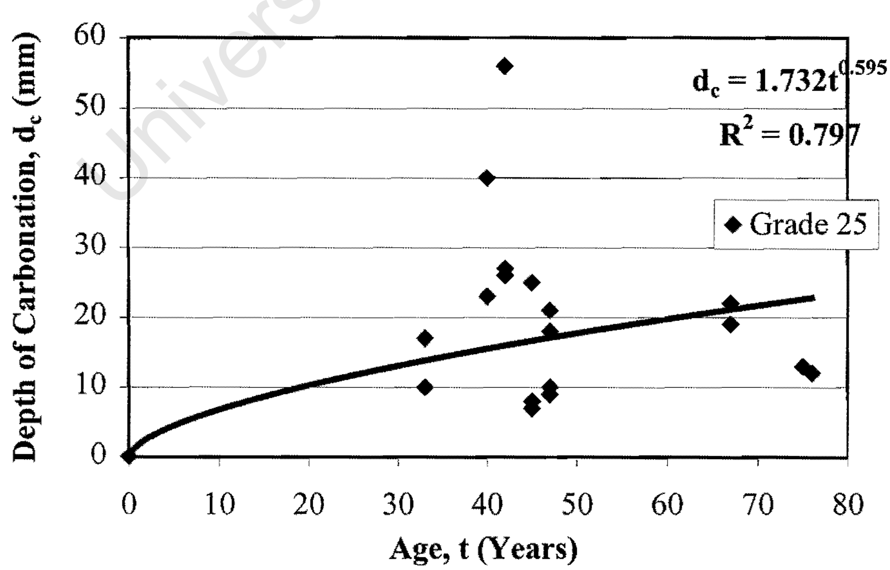


Figure 5.6: Fitted model for Grade 20 exposed elements in Cape Peninsula locality based on power regression of field data before the elimination of gross outliers

There exist outliers (i.e. data points that differ substantially, based on the likelihood that they do not arise from normal statistical randomness, from the rest of the data set). These outliers can affect the model significantly and may be discarded after an investigation of possible causes. A brief discussion on outliers will be provided in section 5.7.2.

The fitted model yields a coefficient of correlation, R^2, of 0.797 (see Figure 5.6). This coefficient indicates how good a trend line (model) is fitted to the data set. A trend line which fits the data set perfectly is equal to 1. It should be noted that this given R^2 and all other R^2 values calculated by the Excel Spreadsheet given in this thesis are based on a transformed (logarithmic) regression model. At this stage, it is difficult to judge whether this fitted power regression model is a good fit or a bad fit trend line, based only on the R^2 value. However, this R^2 value and hence the goodness of fit of the trend line would improve as the gross outliers in this data set are detected by means of residual analysis and then discarded.

There are several ways to detect outliers within a given data set. Most methods involve complicated equations especially for the present type of non-linear analysis. A more simple way was chosen to detect gross outliers, based on a technique making use of the residuals. With the aid of Table 5.2, the technique of detecting outliers by means of residual analysis is explained.

A residual is the difference between the observed dependent value and the predicted value of the fitted model (Berk and Carey (1998)). In other words, the residual in the present analysis is the difference between the measured depth of carbonation, d_c and the predicted value given by the fitted model at the same age. Table 5.2 shows the ages, the (equivalent 28 day cube) compressive strengths, the measured depths of carbonation for the data points, the predicted depths of carbonation given by the fitted model of equation 5.2, the residual for each data point, the residual mean, residual standard deviation (Std. Dev.) as well as the values of two times the positive and negative residual standard deviation (2 x Std. Dev.).

Table 5.2: Method for the detection of gross outlier for Grade 20 exposed concretes in the Cape Peninsula locality, based on power regression analysis of field data

Data Analysis			Detection of Gross Outliers		
Age (t)	**Strength**	**d_c**	**Measured d_c**	**Predicted d_c**	**Residual**
(Years)	**(MPa)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	13.9	3.1
33	27.7	10	10	13.9	-3.9
40	30	40	40	15.6	24.4
40	30*	23	23	15.6	7.4
42	23.1	27	27	16.0	11.0
42	**30***	**56**	**56**	**16.0**	**40.0**
42	30	26	26	16.0	10.0
45	26.1	25	25	16.7	8.3
45	30*	8	8	16.7	-8.7
45	30*	7	7	16.7	-9.7
47	22.5	9	9	17.1	-8.1
47	30*	18	18	17.1	0.9
47	30*	10	10	17.1	-7.1
47	30*	21	21	17.1	3.9
67	30*	19	19	21.1	-2.1
67	30*	22	22	21.1	0.9
75	30*	13	13	22.6	-9.6
76	30*	12	12	22.8	-10.8
				Mean	**2.6**
Note: *refers to assumed strength, see section 5.2.4				**Std. Dev.**	**12.8**
Data in bold indicate outliers				**2x (+Std. Dev.)**	**25.6**
				2x (-Std. Dev.)	**-25.6**

In order to make use of the residual to detect for gross outliers, it is useful to ensure that the residuals are normally distributed. The probability plots of the residuals can verify whether the residuals are normally distributed or not (Bates and Watts (1988)). The procedure for the probability plot of the residuals is given in Table 5.3.

Table 5.3: Spreadsheet for verifying the normality of residuals for grade 20 exposed elements

Residual (mm)	**Residual (sorted)**	**Rank**	**Probability (P<d)**	**NormDist**
0.0	-10.8	1	0.05	0.15
3.1	-9.7	2	0.10	0.17
-3.9	-9.6	3	0.15	0.17
24.4	-8.7	4	0.20	0.19
7.4	-8.1	5	0.25	0.20
11.0	-7.1	6	0.30	0.22
40.0	-3.9	7	0.35	0.31
10.0	-2.1	8	0.40	0.35
8.3	0.0	9	0.45	0.42
-8.7	0.9	10	0.50	0.45
-9.7	0.9	11	0.55	0.45
-8.1	3.1	12	0.60	0.52
0.9	3.9	13	0.65	0.54
-7.1	7.4	14	0.70	0.65
3.9	8.3	15	0.75	0.67
-2.1	10.0	16	0.80	0.72
0.9	11.0	17	0.85	0.74
-9.6	24.4	18	0.90	0.96
-10.8	**40.0**	19	0.95	1.00

Note: The value in bold is the outlier. It is included here because the fitted model also contains this data point

The values of the residuals were obtained from Table 5.2. These residuals were then sorted in ascending order of magnitude, and ranked from the smallest to the largest residual. The purpose of ranking the residuals in ascending order is to obtain a probability distribution, known as a cumulative distribution function. A cumulative distribution function is a function of the cumulative frequency of all observations. A cumulative frequency of observation is defined by the probability of observing a value less than or equal to any particular data point (Chatfield (1970)). In this case, the cumulative frequency ($P \leq d$) is equal to (Chatfield (1970)):

$$\frac{\text{Rank}}{(n+1)} \qquad (5.3)$$

where n is the number of observations (number of residuals in this case, i.e. 19)

Another function is also required to test the normality of the given set of residuals. This is the NormDist function given by the Excel Spreadsheet. This NormDist function gives a normal cumulative distribution function of a given data set based on the mean and standard deviation of that data set. In other words, if the points of the cumulative frequency (P≤ d) of the "sorted" residuals fall on the NormDist function, then the residuals can be regarded as normally distributed. Figure 5.7 shows the probability plot of residuals for this grade of concrete.

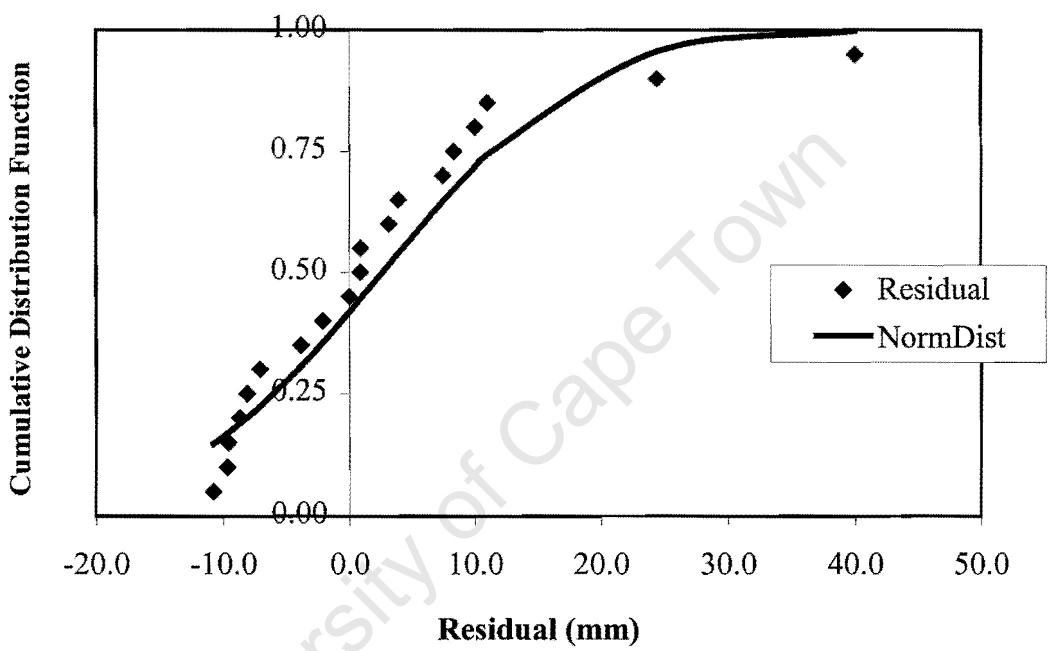


Figure 5.7: The probability plot for residuals of grade 20 exposed concrete elements in Cape Peninsula locality

In Figure 5.7, the residuals for this grade of concrete fall approximately on the NormDist curve. This means that the residuals are not perfectly normally distributed but also they do not deviate substantially from normal distribution. Thus, it is reasonable to infer that the residuals can also be regarded as normally distributed.

Common practice suggests that a data point of a data set can be regarded as a gross outlier if its residual is more than twice the residual standard deviation (if the residuals are normally distributed), since such point differs from the majority (95%) of the data in that data set (Montgomery and Runger (1999)).

By referring to Table 5.2, there was one data point (printed in bold) which had a residual value larger than two times the standard deviation of the residuals. Thus, this data point was regarded as a gross outlier and rejected from the data set.

After the rejection of the outlier, the same procedures were applied to check for further gross outliers in the remaining data until all data had residuals less than two times the standard deviation of the residuals (see Table 5.4, Figure 5.8, Table 5.5 and Figure 5.9). However, due to the limited number as well as the high variability of the data, residual analysis as a means of detecting gross outliers should be used with caution. There is a special case in which only one gross outlier detection was carried out instead of successively. In exposed Grade 30 concretes, the successive detection and elimination of gross outliers based on residual analysis resulted in the elimination of the population group with high carbonation depths (i.e. $\geq$ 15 mm) between 30 and 50 years. The elimination of this population without further investigation could yield a prediction model which may underestimate the carbonation rate for this grade of concrete.

It can be seen from Figure 5.8 and 5.9 that the coefficient of correlation (R^2) improved, after the elimination of outliers. This indicates that the strength of correlation increases with decreasing numbers of outliers. After the second elimination of outliers, there were no further outliers in the data set. The fitted model after the second elimination of outliers was:

$$d_c = 1.579t^{0.584} \tag{5.4}$$

This is taken as the predicted model for grade 20 exposed concrete elements in the Cape Peninsula locality. (Note: three decimal places are given for all numerical terms so as to make proper comparison between models of different grades later.)

Table 5.4: Method for the detection of gross outlier for grade 20 exposed concretes in the Cape Peninsula locality after the first elimination of outlier (1 No.), based on power regression analysis of field data

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	**Strength (MPa)**	**d_c (mm)**	**Measured d_c (mm)**	**Predicted d_c (mm)**	**Residual (mm)**
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	12.9	4.1
33	27.7	10	10	12.9	-2.9
40	**30**	**40**	**40**	**14.4**	**25.6**
40	30*	23	23	14.4	8.6
42	23.1	27	27	14.9	12.1
42	30	26	26	14.9	11.1
45	26.1	25	25	15.5	9.5
45	30*	8	8	15.5	-7.5
45	30*	7	7	15.5	-8.5
47	22.5	9	9	15.9	-6.9
47	30*	18	18	15.9	2.1
47	30*	10	10	15.9	-5.9
47	30*	21	21	15.9	5.1
67	30*	19	19	19.6	-0.6
67	30*	22	22	19.6	2.4
75	30*	13	13	20.9	-7.9
76	30*	12	12	21.1	-9.1
Note: *refers to assumed strength, see section 5.2. Data in bold indicate outliers				**Mean**	**1.8**
				Std. Dev.	**9.2**
				2x (+Std. Dev.)	**18.5**
				2x (-Std. Dev.)	**-18.5**

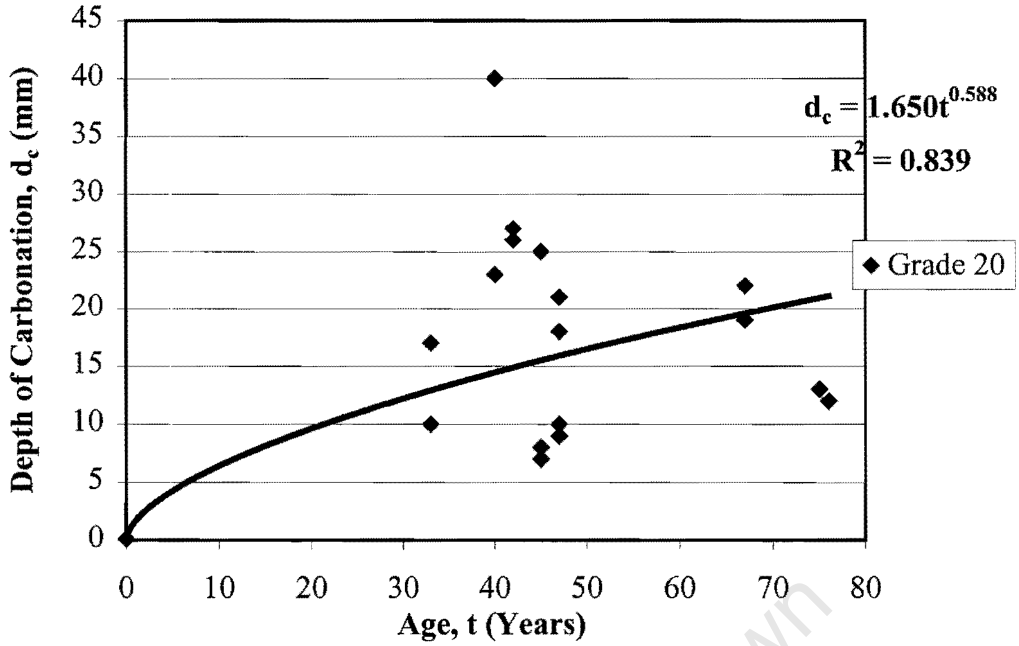


Figure 5.8: A fitted model for Grade 20 exposed elements in Cape Peninsula locality after the first elimination of outliers (1 No.), based on power regression of field data

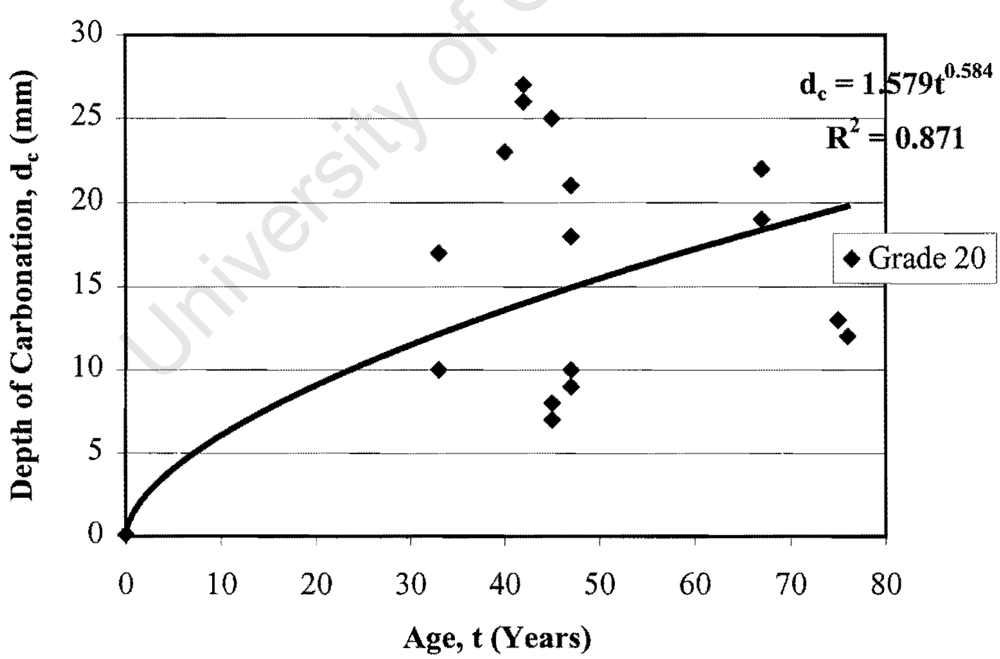


Figure 5.9: A fitted model for Grade 20 exposed elements in Cape Peninsula locality after the second elimination of outliers (1 No.), based on power regression of field data

Table 5.5: Spreadsheet for the detection of gross outlier for grade 20 exposed concrete in the Cape Peninsula locality after the second elimination of outlier (1 No.), based on power regression analysis of field data

Data Analysis			**Detection of Gross Outliers**		
Age (t)	**Strength**	**d_c**	**Measured d_c**	**Predicted d_c**	**Residual**
(Years)	**(MPa)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	12.2	4.8
33	27.7	10	10	12.2	-2.2
40	30*	23	23	13.6	9.4
42	23.1	27	27	14.0	13.0
42	30	26	26	14.0	12.0
45	26.1	25	25	14.6	10.4
45	30*	8	8	14.6	-6.6
45	30*	7	7	14.6	-7.6
47	22.5	9	9	15.0	-6.0
47	30*	18	18	15.0	3.0
47	30*	10	10	15.0	-5.0
47	30*	21	21	15.0	6.0
67	30*	19	19	18.4	0.6
67	30*	22	22	18.4	3.6
75	30*	13	13	19.7	-6.7
76	30*	12	12	19.8	-7.8
				Mean	**1.2**
Note: *refers to assumed strength, see section 5.2.				**Stdev**	**7.2**
				2x (+Stdev)	**14.5**
				2x (-Stdev)	**-14.5**

The same procedures were applied to both grade 30 and 40 exposed concrete elements. The results are shown below. The detailed analyses of these two grades of concrete elements are provided in Appendix B. However, Figures 5.10-5.13 showing all data points before and after the elimination of all gross outliers are given below as these figures can show the reader the need for such an elimination.

• Grade 30 (Exposed elements)

Grade 30 concretes had an equivalent compressive strength in the range of 31 MPa to 40 MPa at 28 days. In this range, 15 bridges with 29 results were studied. The carbonation prediction model (after the elimination of all gross outliers) is:

$$d_c = 1.174t^{0.570} \tag{5.5}$$

• Grade 40 (Exposed elements)

Grade 45 concretes represent concretes with an equivalent cube compressive strength ranging from 41 MPa to 50 MPa at 28 days. In this nominal grade of concrete, 20 results from 9 bridges were analysed. The carbonation prediction model for this grade of concrete is:

$$d_c = 1.293t^{0.550} \tag{5.6}$$

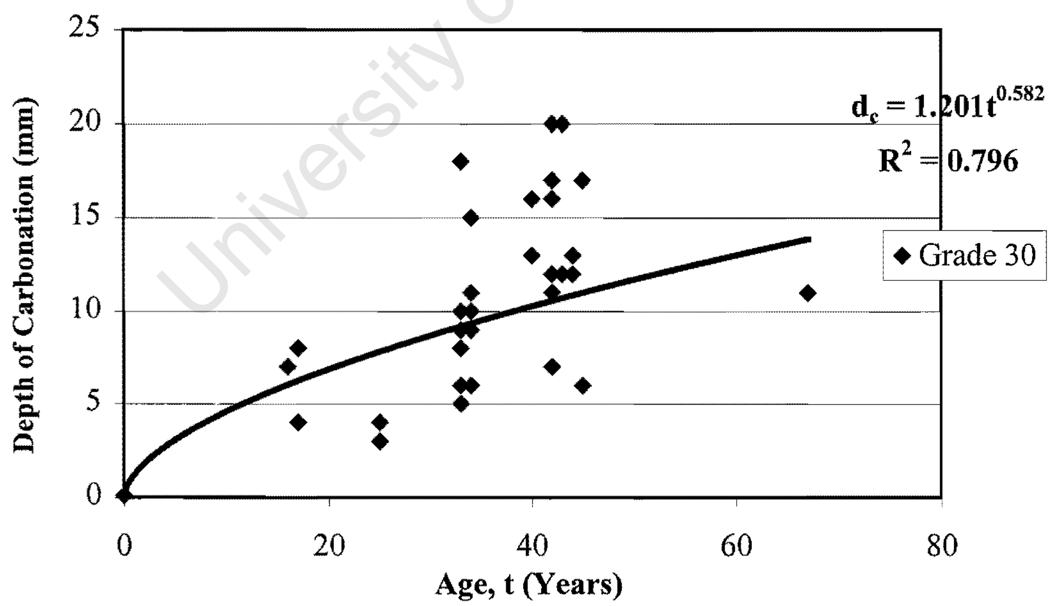


Figure 5.10: A fitted model for Grade 30 exposed elements in Cape Peninsula locality based on power regression of field data before the elimination of outliers

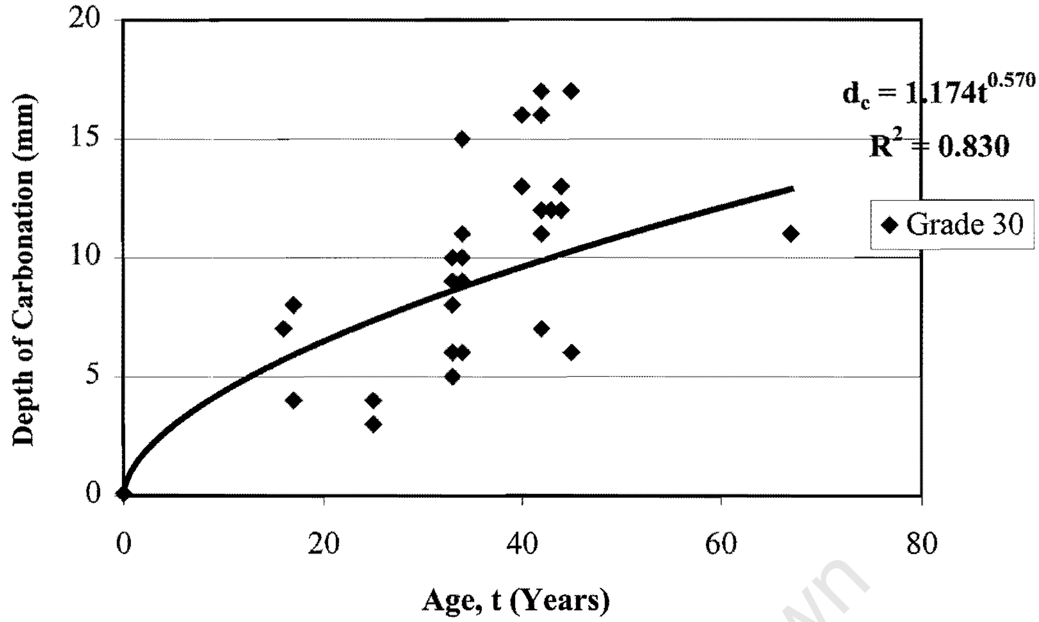


Figure 5.11: A fitted model for Grade 30 exposed elements in Cape Peninsula locality based on power regression of field data after the elimination of all outliers (3 No.)

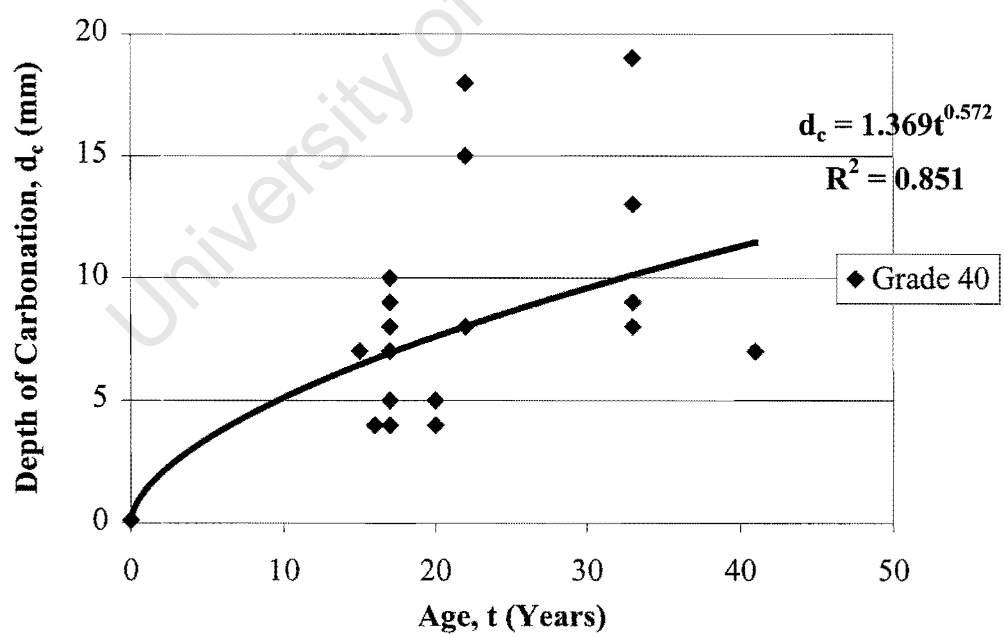


Figure 5.12: A fitted model for Grade 40 exposed elements in Cape Peninsula locality based on power regression of field data before the elimination of outliers

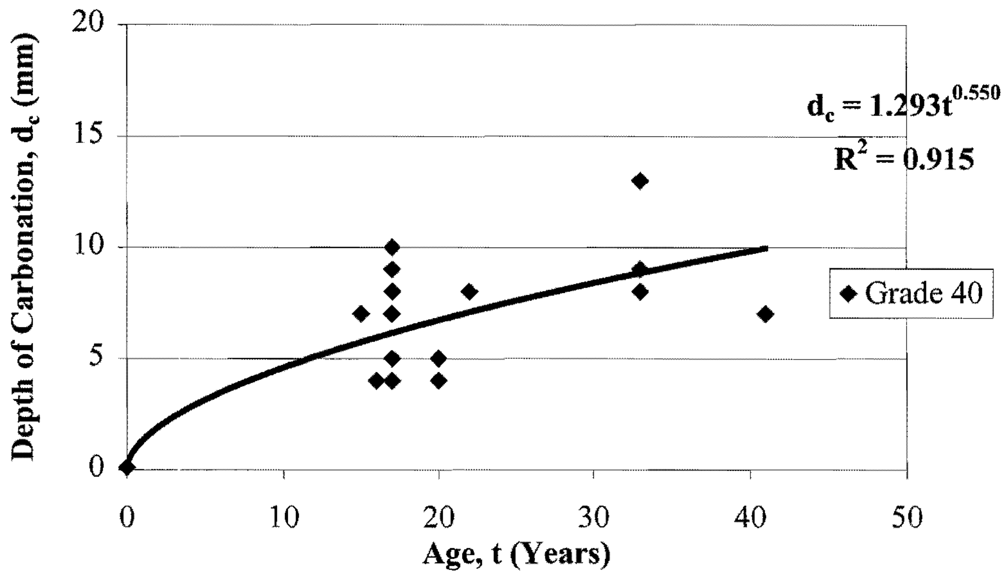


Figure 5.13: A fitted model for Grade 40 exposed elements in Cape Peninsula locality based on power regression of field data after the elimination of all outliers (3 No.)

• Comparison and Discussion

The carbonation coefficient k, and the power series constant n, are summarized for the different grades of concrete (after the elimination of all carbonation depth gross outliers based on residual analysis) in Table 5.6.

Table 5.6: Carbonation coefficients k, and power series constants n, for different concrete grades in the Cape Peninsula locality

Carbonation Prediction Models Derived by Power Regression of Field Data (Units in mm and years)		
Grade	**k**	**n**
20	1.579	0.584
30	1.174	0.570
40	1.293	0.550

From Table 5.6, the carbonation coefficients k, of these 3 grades of concrete vary in a fairly narrow range between 1.174 and 1.579 and the power series constants n, are also in a narrow range of 0.550 to 0.584.

The carbonation coefficient (k) can give a general idea of the rate of carbonation. The larger the k value, the faster the rate of carbonation of concrete. It is interesting to note that the carbonation coefficient k, for Grade 40 concretes is larger than that for Grade 30 concretes, while Grade 20 concretes have the highest value. This may indicate that, by looking at k value alone, the rate of carbonation for grade 20 concretes are the fastest whilst the rate of carbonation for grade 40 is faster than that of grade 30. Under the similar environmental effects for which the samples were cored from bridges in the Cape Peninsula locality, the rate of carbonation of concrete is thus mainly governed by the material effects such as permeability of concrete. The above results may contradict the fact that grade 40 concretes are generally less permeable than grade 30 concretes and therefore the rate of carbonation for grade 40 concretes should be slower, not faster than that of grade 35 concretes. However, the power series constants n for these three grades of concretes are not the same, and thus it is not meaningful to purely compare the k values to determine which grade of concrete has the fastest rate of carbonation.

Considering the power series constants n, Grade 20 concretes have the highest value whilst Grade 40 concretes have the lowest value, with an intermediate n-value for Grade 30 concretes. This may indicate that Grade 20 concretes have the highest rate of carbonation and Grade 40 concretes have the lowest rate while the rate of carbonation of Grade 30 is intermediate. However, owing to the same reasoning as for the k values, the direct comparison of n values may not be meaningful.

For comparison purpose, it is more sensible to plot the depths of carbonation predicted by the models for each concrete grade. Figure 5.14 shows the predicted depth of carbonation with time of exposure based on the derived carbonation coefficients k, and power series constants n. The tabulated depths of carbonation for each grade of concrete are given in Appendix B. It should be noted that although the derived prediction models can predict the depths of carbonation for any long period of time, say, 100 years, the accuracy for such a long-time prediction is questionable. This is because these prediction models are based on field bridge data between the ages of 15 and 76 years, which the majority of data aged between 15 and 50 years. Therefore, it is advisable to use these prediction models to predict the depth of carbonation up to a maximum age of 60 years.

Figure 5.14 clearly shows that the depth of carbonation increases with time of exposure, as expected due to ongoing diffusion of carbon dioxide; also the rates of carbonation for these concrete grades decrease with time.

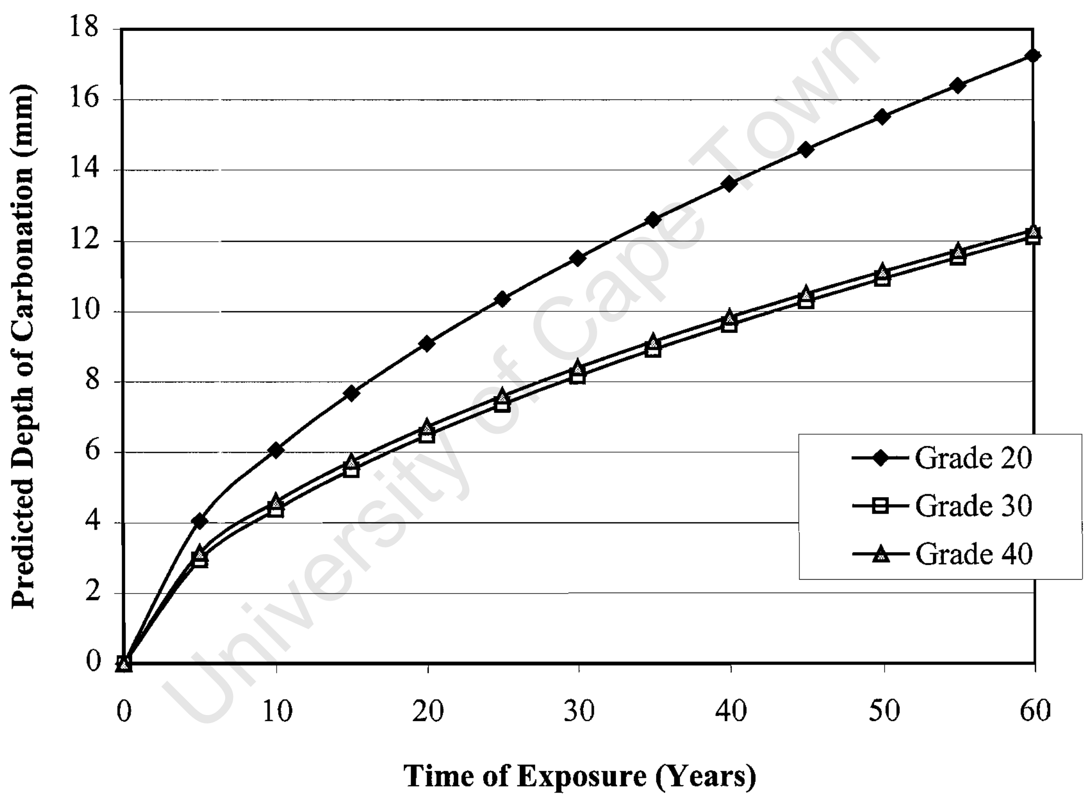


Figure 5.14: Carbonation depths prediction based on power regression of field data

Grade 20 concretes exhibit the highest rate of carbonation, and have the greatest depth of carbonation at any given time. This is expected as the material factors (such as higher water/cement ratio and hence a more porous cover concrete) of Grade 20 concretes favour the process of carbonation.

The rates of carbonation for grade 30 and 40 concretes are practically the same. This may be due to the following reasons:

Neville (1995) reported the relationship between permeability and water/cement ratio for cement pastes as shown in Figure 5.15. This figure can be taken to be indicative of the relative permeability relationship for a mature concrete, since permeability is strongly dependent on the water/cement ratio of the concrete.

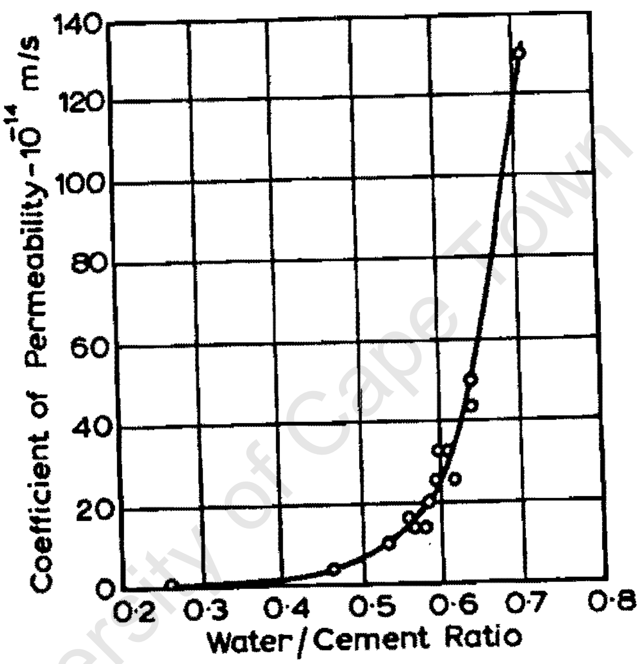


Figure 5.15: Relation between permeability and water/cement ratio for mature cement pastes (93% of cement hydrated) (Neville (1995)).

Figure 5.15 indicates that permeability becomes very sensitive at water/cement ratio values above 0.6. Below this value, permeability varies moderately, but above this value, permeability increases very rapidly. Thus, from Figure 5.17, Grade 20 concretes with a water/cement ratio of 0.73 (Fulton (1977)) have the highest permeability and therefore the rate of carbonation should be the highest as well. On the other hand, the permeability for grade 30 and grade 40 concretes with water/cement ratios of 0.59 (Fulton (1977)) and 0.49 (Fulton (1977)) have only a small difference in the permeability. This suggests one of the possible reasons why the rate of carbonation for these two grades of concretes is practically the same.

The second possible reason may be due to the change in cement characteristics with time. Figure 5.16 shows compressive strength in relation to the age of bridges from which the data were obtained in the present locality:

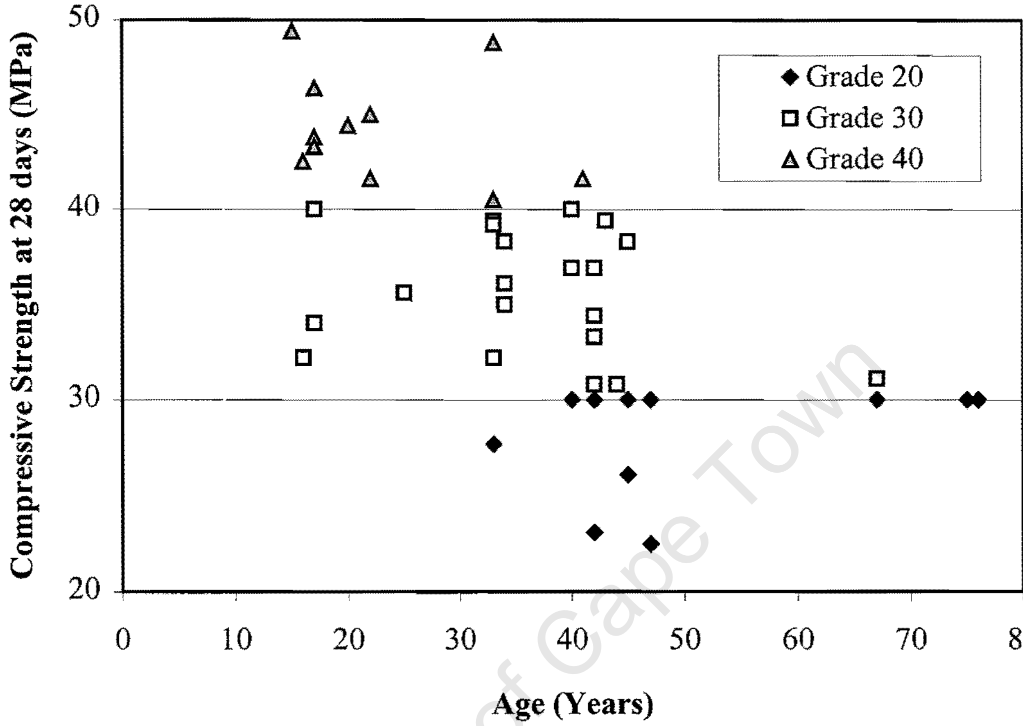


Figure 5.16: Age of data for Grade 20, 30 and 40 exposed concrete elements in the Cape Peninsula locality

It can be seen that the data for Grade 20 and 30 concretes come from bridges of roughly the same ages. On the other hand, the majority of the data for Grade 30 concrete are older than the majority of the data for Grade 40 concretes. Thus, these two grades of concrete may represent different cements in terms of characteristics such as fineness. A discussion on the change in cement fineness with time and the possible associated effects on carbonation rate will be provided in the section analysing the data of Durban locality as there exists a clearer difference in carbonation rates for concretes manufactured using old and modern cements.

It should be noted that the ages of the data range from 15 to 76 years. In other words, no early-age data were used in the derivation of these models. This could be a weakness for these prediction models, as it may cause the models to be biased in favour of later age values (see Figure 5.17).

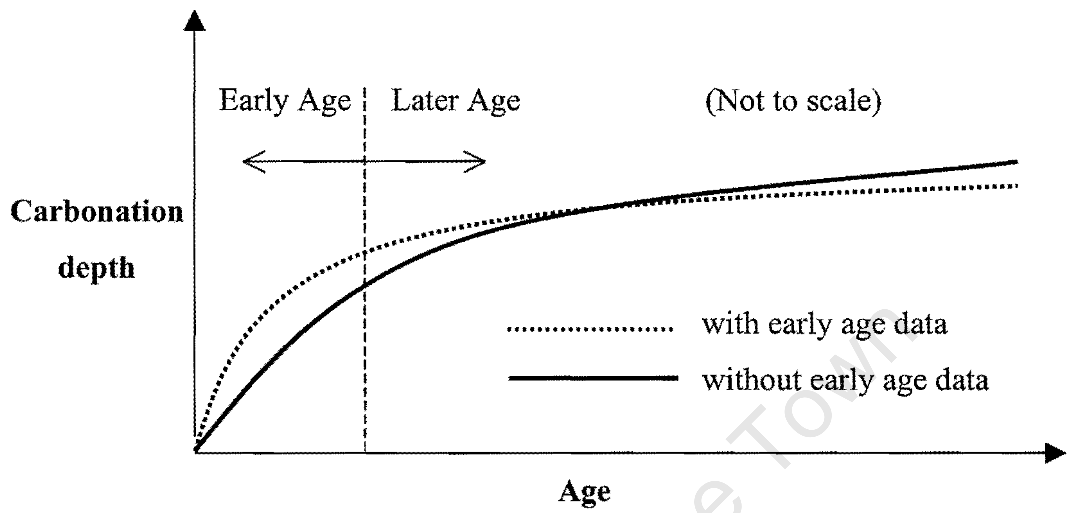


Figure 5.17: Schematic of prediction models with and without early age data

It is important to point out that the rate of carbonation is highest in the early age period and then slows down as for example, more and more calcium carbonate is deposited in the pore structure. Therefore, it is desirable to derive a carbonation prediction model based on the inclusion of both early-age and later age data to allow the change in rate of carbonation as shown in Figure 5.17. This leads to a modification of this method in which the obtained bridge data are combined with early-age laboratory data.

(b) Incorporation of Early Age Lab Data

The prediction models given above rely heavily on later age field data. To improve these prediction models, it is necessary also to have early-age data. Therefore it was decided to incorporate early-age carbonation data into later age field data with the same analytical procedures, if early- age data were available. There are limited early-age data in the literature from Mackechnie (1999). His data were not derived from bridges but were laboratory data from concrete samples which were exposed to a real environment, outside the laboratory at the University of Cape Town (the background information of Mackechnie's investigation was provided in section 3.4.2 (h)). That is to say, although his data were obtained from laboratory specimens and not in-situ bridge data, the samples were all exposed to the Cape Peninsula climatic conditions instead of controlled conditions, thus they may be incorporated into the in-situ bridge data, on the grounds that the climatic conditions were similar. In addition, the inclusion of his data into the in-situ data is on the basis of water/cement ratios, not on compressive strength. Therefore, although his data were based on the cements of late 1990s and the cement properties of his data may not be the same as that of the in-situ bridge data (as mentioned in the previous section), the associated effects on carbonation rates are presumably be minimized.

Mackechnie's data were from samples aged between one to six years. Two grades of concrete in his investigation could be incorporated into the present analysis, namely Grade 20, and Grade 40. The binder type of these two concrete grades was ordinary Portland cement which was the same as the assumed binder type for the bridge data. The concrete grades, corresponding water/binder ratio, curing regime and depths of carbonation measured after 1, 4 and 6 years of exposure for the laboratory data are listed in Table 5.7.

Table 5.7: Early-age laboratory data (Mackechnie (1999)).

Binder Type	Grade (MPa)	w/c ratio	Initial Curing	Carbonation depth (mm) at		
				1 year	4 years	6 years
OPC only	20	0.83	Moist	7.5	13	14
			Dry	8.5	14	15.5
	40	0.56	Moist	4.5	5	6.5
			Dry	5.5	6	7.5

Two curing regimes were employed. "Moist" means the specimens were moist cured at 90% RH and 23°C for the initial seven days while "dry" refers to the curing conditions of 50% RH and 23°C for the initial seven days. Moist cure signifies good site practice while dry cure is equivalent to poor constructional practice. After the initial curing, the specimens were then exposed to outdoor exposure.

Only moist cured samples were used for the following analysis and dry cured samples were excluded. This is because dry cured samples do not represent any definable level of site curing.

As a point of interest, by comparing the moist and dry cured data in Table 5.7, the dry cured data always had marginally higher depths of carbonation than the moist cured samples, for the same concrete grade and at the same time interval. This illustrates the importance of curing for carbonation. The differences in the depth of carbonation between moist cured and dry cured data would be more significant if the laboratory specimens were exposed in low rainfall season (i.e. summer in Cape Town) because of the absence of rain water for the specimens to allow further curing.

The Grade 20 laboratory data are included in the Grade 20 field data, whilst Grade 40 laboratory data are incorporated with both Grade 30 and Grade 40 field data. This is because the Grade 40 laboratory data had a water/cement ratio of 0.56 which is within the range of water/cement ratios for Grade 30 field concretes as shown in Table 5.8. On the other hand, the water/cement ratio for laboratory data is only slightly higher than that of the upper value of water/cement ratio of 0.53 (i.e. compressive strength of 41 MPa) for grade 40 field data; also according to Neville (1995) (see Figure 5.15), the permeability between the two are very similar; and in addition, it is necessary to have early age data in order to condition the prediction model (as shown in Figure 5.17). It should be noted that, as mentioned previously, the inclusion of early age data is based on water/cement ratios, thus the difference in carbonation rates between Mackechnie's data and field data (arising from different cement properties) may be assumed to be insignificant.

Table 5.8: Water/cement ratios for the field concrete grades

Compressive Strength (MPa)	w/c Between	Nominal Grade	w/c
21 - 30	0.81 and 0.65	Grade 20	0.73
31- 40	0.64 and 0.54	Grade 30	0.59
41 - 50	0.53 and 0.45	Grade 40	0.49

As noted previously, in order to improve the prediction models derived from the first approach, the laboratory data are incorporated into the bridge data. The analytical procedures including regression, detection and elimination of outliers are exactly the same as in the first analysis, therefore the detailed analytical procedures are given in Appendix C. The final scatter plots for each concrete grade after the detection and elimination of all outliers are shown in Figures 5.18 – 5.20.

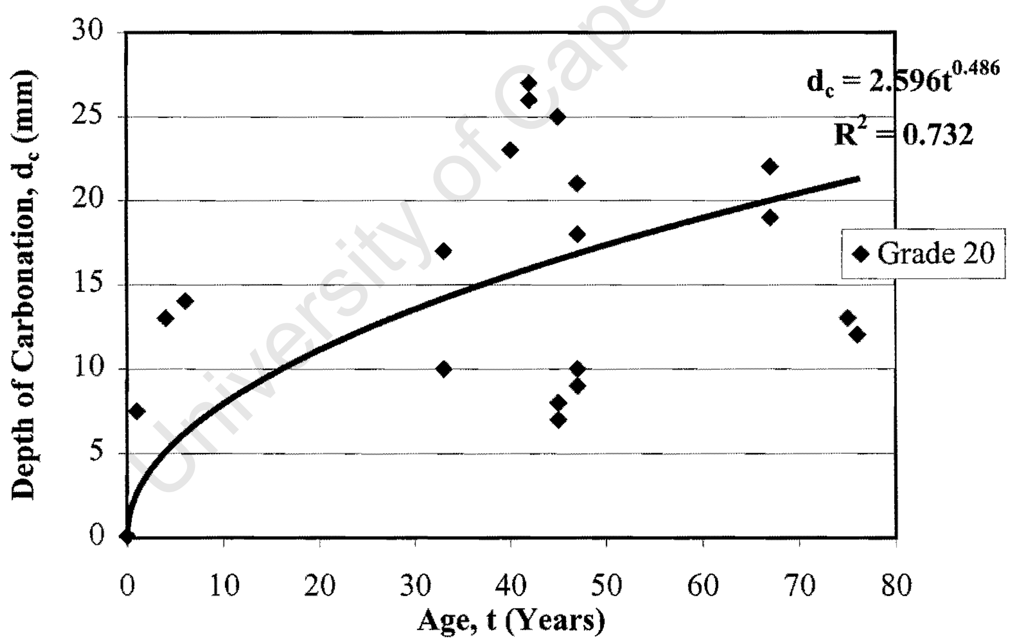


Figure 5.18: Fitted model for Grade 20 exposed elements in Cape Peninsula locality based on the incorporation of early age lab data after the elimination of all outliers (2 No.)

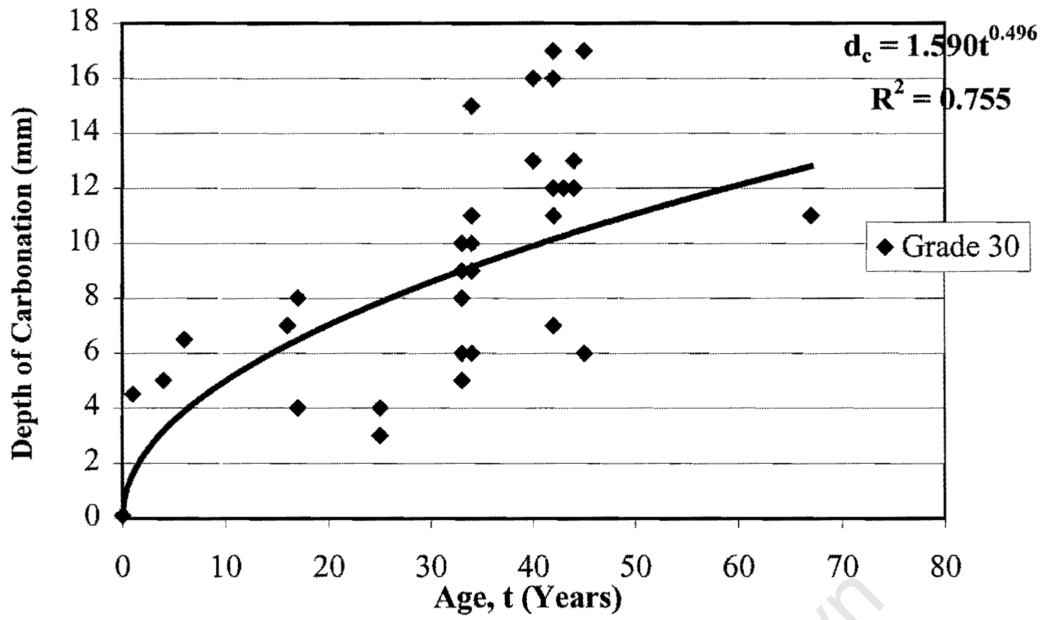


Figure 5.19: Fitted model for Grade 30 exposed elements in Cape Peninsula locality based on the incorporation of early age lab data after the elimination of all outliers (3 No.)

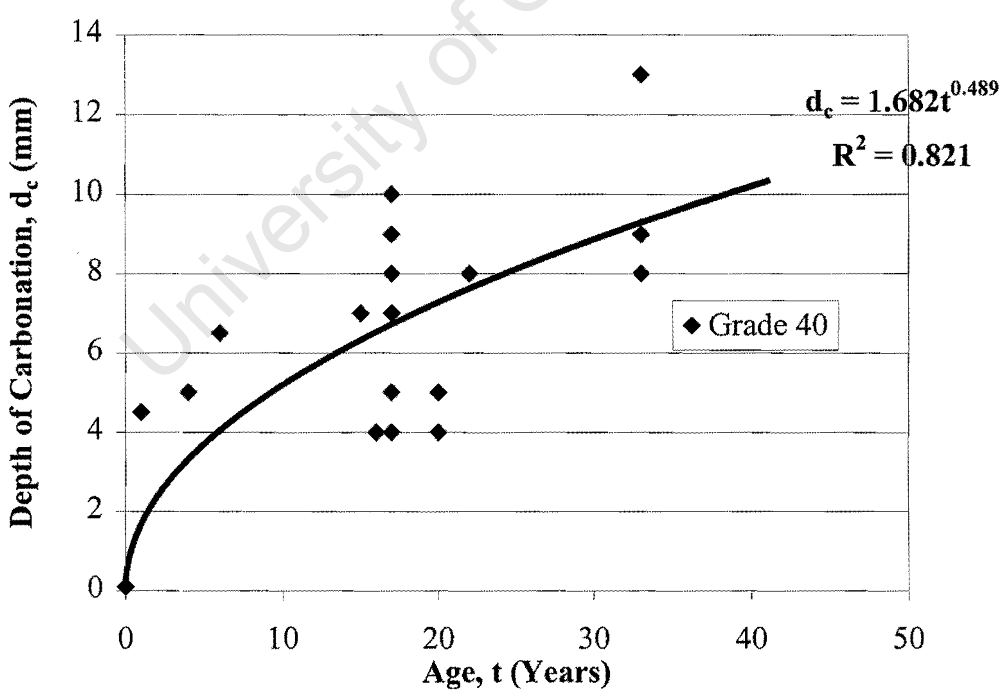


Figure 5.20: Fitted model for Grade 40 exposed elements in Cape Peninsula locality based on the incorporation of early age lab data after the elimination of all outliers (3 No.)

• Comparison and Discussion

It should be mentioned that the outliers identified from this approach were identical to those identified in the first analysis. This is attributed to the fact that the nature of the two approaches is essentially the same as well as the fact that the outliers differed substantially from the rest of the data. A discussion on the outliers will be in section 5.7.2.

Table 5.9 lists the carbonation coefficients, k and the power series constants, n for Grade 20, 30 and 40 concretes obtained from this analysis and Figure 5.21 shows the predicted depth of carbonation versus time of exposure for these three grades of concrete based on the results. Details are given in Appendix C.

Table 5.9: Carbonation coefficients and power series constants for concretes, combined field and lab data

Carbonation Prediction Models Derived by Incorporation of Early Age Lab Data		
Grade	**k**	**n**
20	2.596	0.486
30	1.590	0.496
40	1.682	0.489

From this approach, it should be noted that the power series constant n, for these three concrete grades is very close to the theoretical value of 0.5 which is based on Fick's law of diffusion (see section 3.4.1). Again, the carbonation coefficient (k) for Grade 20 is the largest and Grade 30 is the smallest and Grade 40 is higher than that of Grade 30 concretes. As reasoned in the first analysis, the direct comparison of these values between these concrete grades is not meaningful. A better means of comparison is given in Figure 5.21.

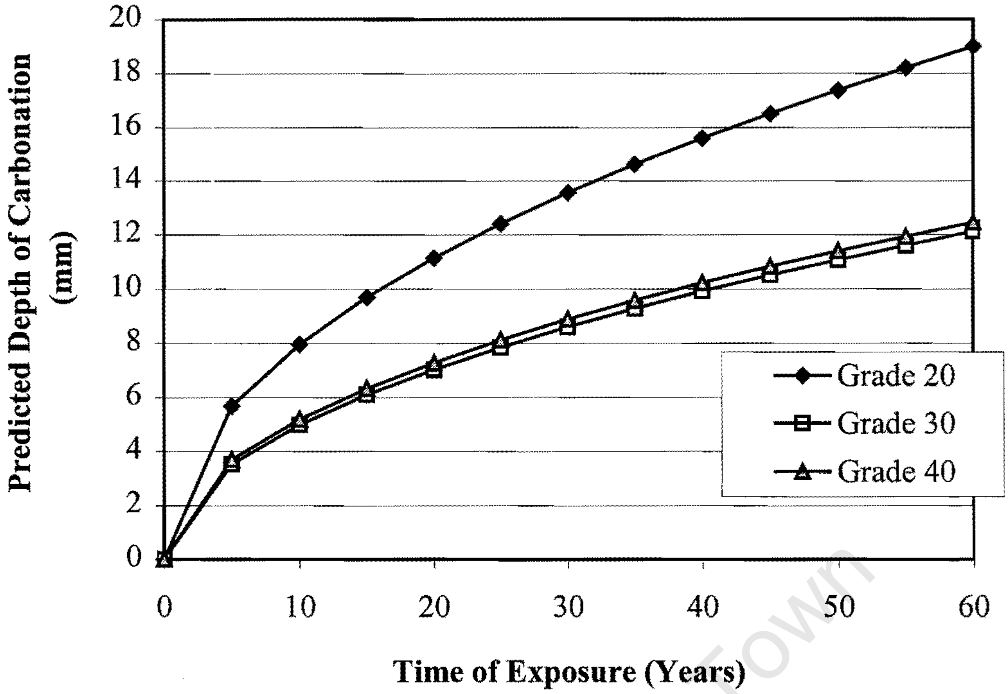


Figure 5.21: Carbonation depth prediction based on incorporation of early age laboratory data

The prediction above is probably reasonably reliable up to about 60 years, as explained in the first analysis, due to the ages of the majority of data in the analysis ranging from 15 to 50 years. The prediction for greater than 60 years would have a problem of over-extrapolation which may affect the accuracy of the prediction.

Grade 20 concretes exhibit the greatest depth of carbonation compared with the other two grades. Grade 30 and Grade 40 concretes have practically the same depth of carbonation. This may be reasoned due to the similar permeability of these two concrete grades as illustrated by Figure 5.15.

In essence, the nature of these two analyses is the same. They both use the Excel Spreadsheet to fit a trend line to the data of a given grade of concrete. From the fitted trend line, gross outliers can be detected and hence eliminated. The "final" fitted trend line after the elimination of all gross outliers can be viewed as the prediction model for that grade of concrete. The only difference between these two analyses is the data themselves. The former analysis is based on later-age data only without early-age data whilst the latter analysis included the early-age lab data with the later-age data. A question arises as to how much difference in the prediction models derives from these two analyses. Table 5.10 shows the carbonation prediction models derived only from later age field data, and incorporation of early-age laboratory data for Grade 20, 30 and 40 concretes. Figure 5.22 – 5.24 compare the prediction models derived by these analyses for each concrete grade.

Table 5.10: Comparison of the results between power regression of field data and incorporation of early-age laboratory data

Grade of Concrete	Method of Analysis					
	(a) Field Data Only			(b) Incorporation of Early-Age Laboratory Data		
	k	n	R^2	k	n	R^2
Grade 20	1.579	0.584	0.871	2.596	0.486	0.732
Grade 30	1.174	0.570	0.830	1.590	0.496	0.755
Grade 40	1.293	0.550	0.915	1.682	0.489	0.821

The carbonation coefficients k increase for all three grades of concrete by including early age laboratory data. On the other hand, the power series constants n reduce for all three grades of concrete. The correlation coefficients R^2 decreased by including a limited number of early age lab data and this reflects the fact that the early age data were generally somewhat higher than the later age model would predict. Although there is very little difference between the carbonation depth predictions for each of the concrete grades derived by the above analyses as shown in Figures 5.22 – 5.24, because of the very limited early-age data relative to the later-age field data, this still indicates two important facts in modelling the rate of carbonation.

The first fact is the increase in the value of carbonation coefficient (k) shows that the rate of carbonation occurs most rapidly at the early ages. This is partly because the outer part of the cover concrete known as the curing affected zone is generally more porous, and this zone is where carbonation of concrete takes place at early ages.

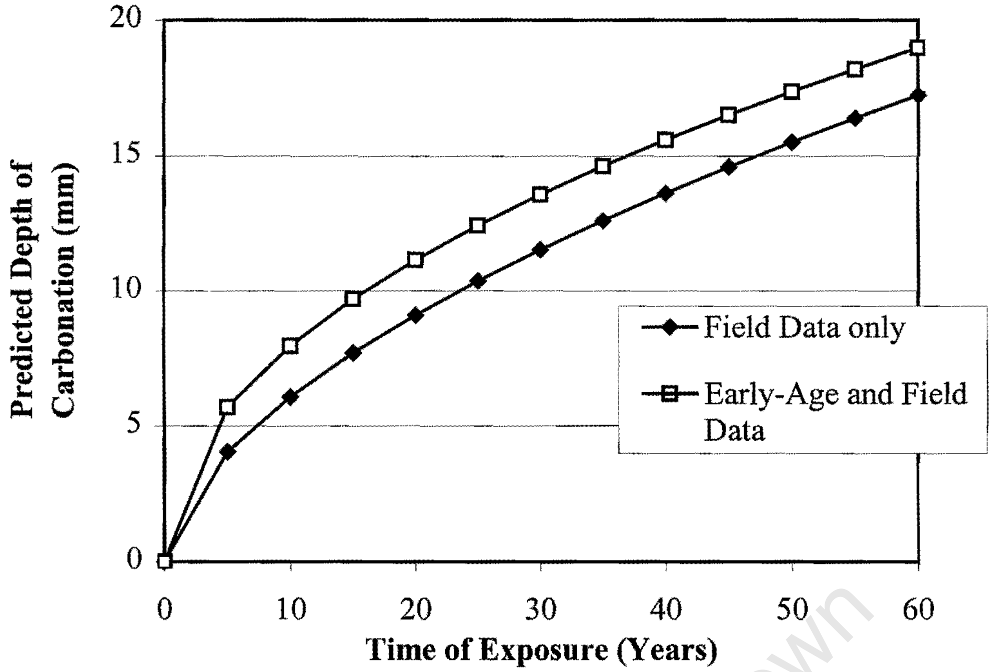


Figure 5.22: Carbonation prediction based on later-age field data only and combined early-age and field data for Grade 20 exposed elements in the Cape Peninsula locality

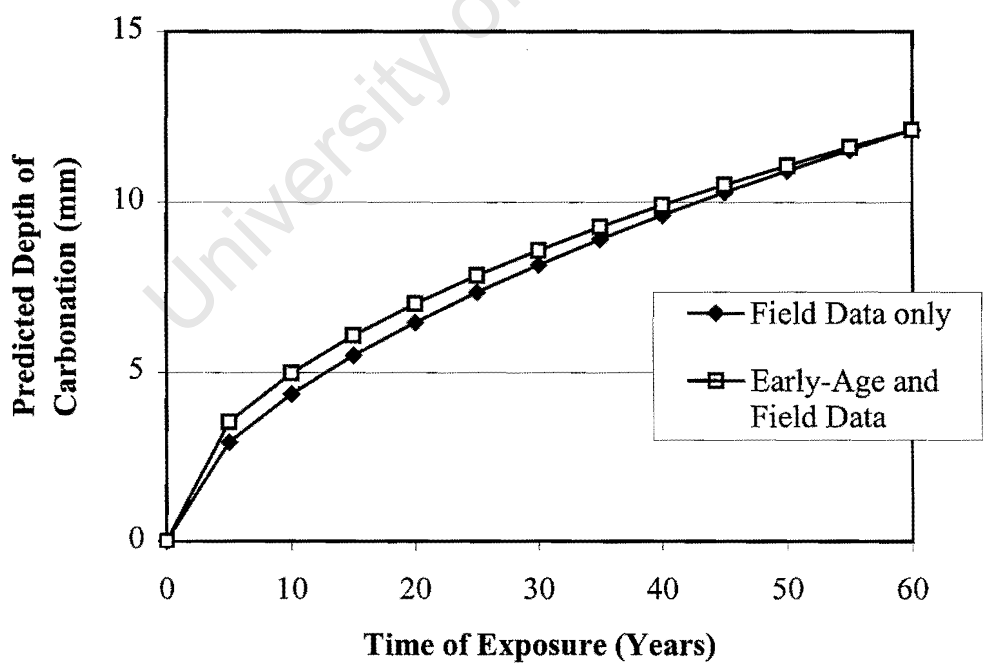


Figure 5.23: Carbonation prediction based on later-age field data only and combined early-age and field data for Grade 30 exposed elements in the Cape Peninsula locality

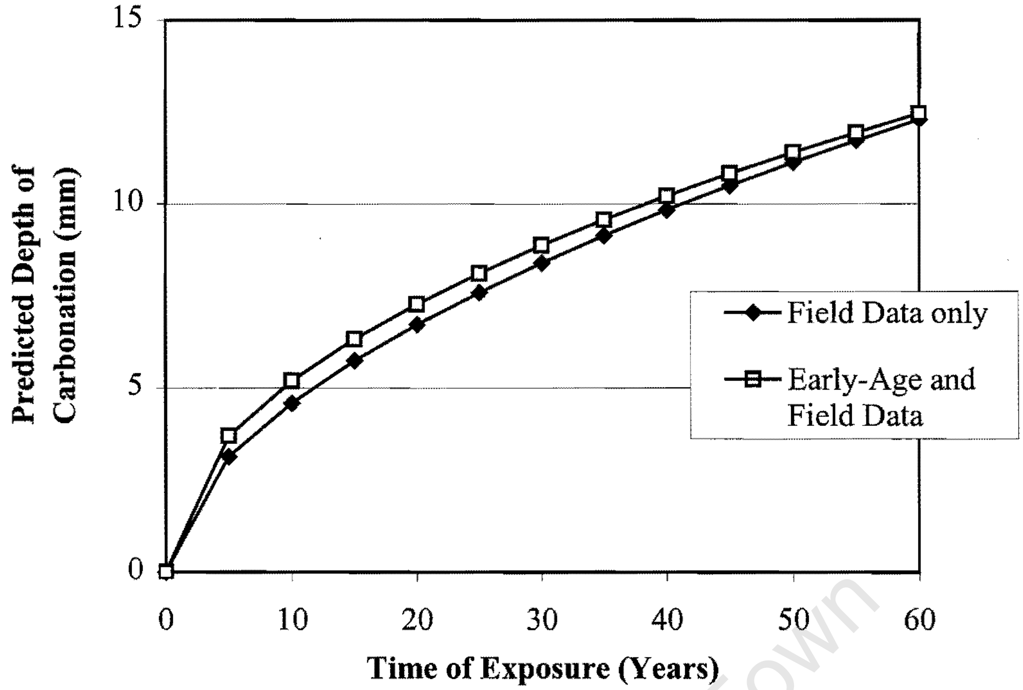


Figure 5.24: Carbonation prediction based on later-age field data only and combined early-age and field data for Grade 40 exposed elements in the Cape Peninsula locality

The second fact is the decrease in the value of the power series constants (n) indicates that the rate of carbonation decreases with time of exposure. This occurs because the formation and deposition of calcium carbonate through the process of carbonation densifies the pore structure and limits the passage of carbon dioxide. Furthermore, the pore structure of concrete improves with depth from the surface, thus also hindering the passage of carbon dioxide into concrete (Bakker (1988)). Therefore, the rate of carbonation should decrease with time.

Generally speaking, the inclusion of early-age data into the analysis of the later-age field data improves the prediction model by changing the curve so as to provide better prediction at both early and later ages. As explained, owing to only a few early age data being available, the effects on the curve are not very pronounced. Nevertheless, the later-age prediction model may tend to overestimate long-term carbonation depths by providing n values that are higher than the conventionally accepted value of 0.5.

In addition, one other disadvantage of the lack of early-age data is the assignment of the non-zero "initial" point, as mentioned previously, in order for Excel Spreadsheet to perform a regression. Table 5.11 lists the outcomes given by several assigned non-zero "initial" points for Grade 20 exposed concretes, for illustration purposes.

Table 5.11: Outcomes for different non-zero "initial" points

Time (t)	**Carbonation Depth (d_c)**	**Carbonation Coefficient (k)**	**Power Series Constant (n)**	**Coefficient of Correlation (R^2)**
(Years)	(mm)	(mm/year^n)		
0.01	0.01	0.623	0.884	0.903
0.01	0.1	1.750	0.613	0.823
0.1	0.1	0.743	0.838	0.817
1.1×10^{-7}	1.1×10^{-7}	0.481	0.953	0.984

It can be seen that the "initial" point has an effect on the terms (k and n) of carbonation prediction model as well as the coefficient of correlation (R^2). It should be noted that the most acceptable "initial" point should be (0;0) as the carbonation depth of a concrete should be 0 mm before being exposed to the atmosphere. However, Excel cannot fit a power trend line to a data set which contains a zero value due to the transformation from a non-linear to linear logarithmic model. Based on the understanding of the carbonation of concrete (which suggests n should be close to 0.5, see section 3.4.1) and the principle of statistical correlation (which requires R^2 close to 1), the "initial" point chosen was (0.01 years; 0.1 mm). Nevertheless, the predicted depths of carbonation for the period say up to 80 years (the suggested period for prediction), between the predictions based on these "initial" points do not differ too greatly as shown in Figure 5.25.

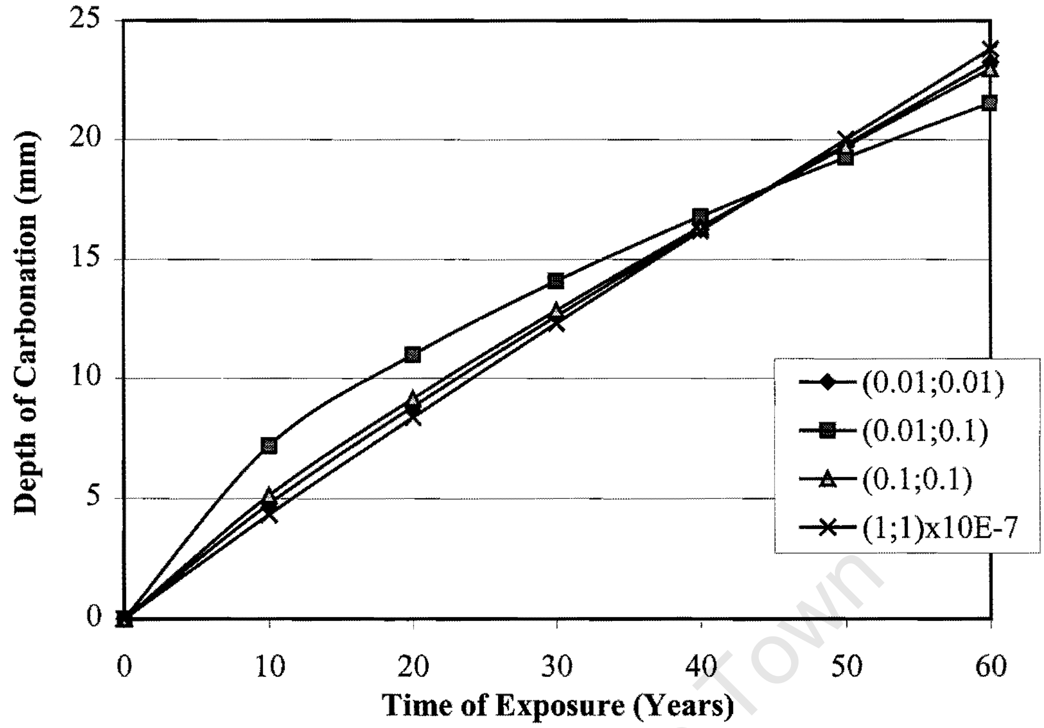


Figure 5.25: Carbonation predictions based on different "initial" points.

Due to the number and ages of the available data as well as the necessity of the assignment of a non-zero "initial" point, these shortcomings cause difficulties and inaccuracy in optimising the two variables (k and n) in the prediction model. Therefore, a different approach is considered – that of the "Method of Least Squares".

PART B: METHOD OF LEAST SQUARES

Method of Least Squares

In the previous section, it was shown that both the coefficient of carbonation, k and the power series constant, n of the prediction model changed by the assignment of the non-zero "initial" point, as well as by including the early age data in the power regression analysis of the later age data. Thus there is a problem of "bias" of the prediction model if only later age data is considered.

Therefore, a different analysis method was used to seek to better understand the later age data. Early age data are excluded in this analytical method due to the change in cement properties and hence different rates of carbonation (see Chapter 6 for more detail). For addition, it was desired to derive a prediction model that would have a more rigorous statistical basis. The method chosen was the Method of Least Squares. A series of fixed "n" values is chosen, and employed to derive the prediction model. The series of n values chosen were: 0.3, 0.4, 0.5 and 0.6. It should be noted that, as given in section 3.4.1, n should be equal to 0.5 under ideal and steady (uniform environment and pore structure) conditions. However, n will decrease under periodic wetting whilst n may increase in cases of deteriorated concrete. Therefore, it was decided to investigate those n values which are lower and higher than the theoretical value.

Through this method of analysis, the most appropriate n value among the selected values, as well as the carbonation coefficient k, can be established by comparing the sums of the square of residuals (e^2) and the predicted depths of carbonation obtained from the fixed series of n. In addition, a value of n can also be selected based on an understanding of the physical conditions for the process of carbonation. The detailed analytical procedures for Grade 20 concretes are provided below as an example (including the principle, governing equations and the application of these equations), while the procedures for the other two concrete grades will be given in Appendix D since the procedures are exactly the same.

• Grade 20 (Exposed elements)

The principle of least squares in the context of the present analysis is to minimize the sum of the square of residuals (error) between the predicted depth of carbonation and the measured carbonation depth (d_{ci}) at any given time (t_i) by optimising the variables (i.e. k and n) of the fitted model (i.e. $d_c = kt^n$, as given in equation 5.1) based on differentiation. Since the value of n is selected in the present analysis, only one variable k needs to be optimised. From this principle of least squares, the optimised k is given by (the derivation of this equation is given in Appendix D):

$$k = \frac{\sum_{i=1}^{n} d_{ci} t^{n}}{\sum_{i=1}^{n} t^{2n}} \qquad (5.7)$$

where k is the carbonation coefficient

d_{ci} is the measured depth of carbonation

t_i is the time of measuring the depth of carbonation

n is the power series constant

Table 5.12 shows the procedures of obtaining k by the above equation. In this table, the chosen n value is 0.3. The data that were used in the analysis consisted of later age field data only.

According to Equation (5.7), k is equal to:

$$k = \frac{854.92}{165.74}$$

$$= 5.16 \text{ mm/yr}^{0.3}$$

"Predicted" refers to the predicted depths of carbonation and is given by:

$$\text{"Predicted"} = 5.16t^{0.3} \qquad (5.8)$$

Table 5.12: The evaluation of k and the sum of squares of residuals for exposed Grade 20 concrete in the Cape Peninsula locality when n is chosen to be 0.3

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\, t_i^{0.3}$	Predicted	Residual	Residual^2
33	27.7*	17	2.85	8.15	48.53	14.7	2.3	5.2
33	27.7	10	2.85	8.15	28.55	14.7	-4.7	22.3
40	30*	23	3.02	9.15	69.56	15.6	7.4	54.8
42	23.1	27	3.07	9.42	82.86	15.8	11.2	124.8
42	30	26	3.07	9.42	79.79	15.8	10.2	103.4
45	26.1	25	3.13	9.82	78.33	16.2	8.8	78.1
45	30*	8	3.13	9.82	25.06	16.2	-8.2	66.6
45	30*	7	3.13	9.82	21.93	16.2	-9.2	83.9
47	22.5	9	3.17	10.08	28.57	16.4	-7.4	54.4
47	30*	18	3.17	10.08	57.13	16.4	1.6	2.6
47	30*	10	3.17	10.08	31.74	16.4	-6.4	40.6
47	30*	21	3.17	10.08	66.66	16.4	4.6	21.4
67	30*	19	3.53	12.46	67.08	18.2	0.8	0.6
67	30*	22	3.53	12.46	77.67	18.2	3.8	14.4
75	30*	13	3.65	13.34	47.47	18.8	-5.8	34.1
76	30*	12	3.67	13.44	44.00	18.9	-6.9	47.8
			Sum	**165.74**	**854.92**	**Mean**	**0.1**	**755.0**
						Stdev	**7.1**	
* assumed values see section 5.2.4						**2x(+Std.Dev)**	**14.2**	
						2x(-Std.Dev)	**-14.2**	

Note: This table shows the final results after the elimination of all outliers (2 No.)

The residual is calculated by subtracting the "predicted" d_c from measured d_c. Carbonation depth gross outliers were detected when the residuals of any carbonation data were greater than two times the standard deviation of the residuals, using the same procedures as in the previous analysis.

The sum of the squares of residuals for this concrete grade with n as 0.3 is 755.0. This value is important in the sense that it aids the selection of the best fit k and n values for the given data set. This is because the "statistical" best fit k and n values are the ones which yield the smallest sum of squares of residuals. However, the decision on the best fit k and n values should also integrate the understanding of the physical process of carbonation into the consideration.

The same procedures were applied for the other selected series of n and the results are shown in Table 5.13 and Figure 5.26.

Table 5.13: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 20 concretes in the Cape Peninsula locality

n	k	e^2
0.3	5.16	755.0
0.4	3.47	782.7
0.5	2.33	816.6
0.6	1.57	856.8

Table 5.14 and Figure 5.26 show the predicted depths of carbonation given by the above k and n values as well as the in-situ data. The results for the Grade 30 and 40 concretes are shown below as well. A comparison and discussion of these results will be provided later.

Table 5.14: Predicted depths of carbonation for the chosen n values for exposed Grade 20 concretes in the Cape Peninsula locality

Time, t	Predicted Carbonation Depth, d_c (mm)			
(Years)	n = 0.3	n = 0.4	n = 0.5	n = 0.6
0	0.0	0.0	0.0	0.0
20	12.7	11.5	10.4	9.5
40	15.6	15.2	14.7	14.4
60	17.6	17.8	18.0	18.3
80	19.2	20.0	20.8	21.8
100	20.5	21.9	23.3	24.9

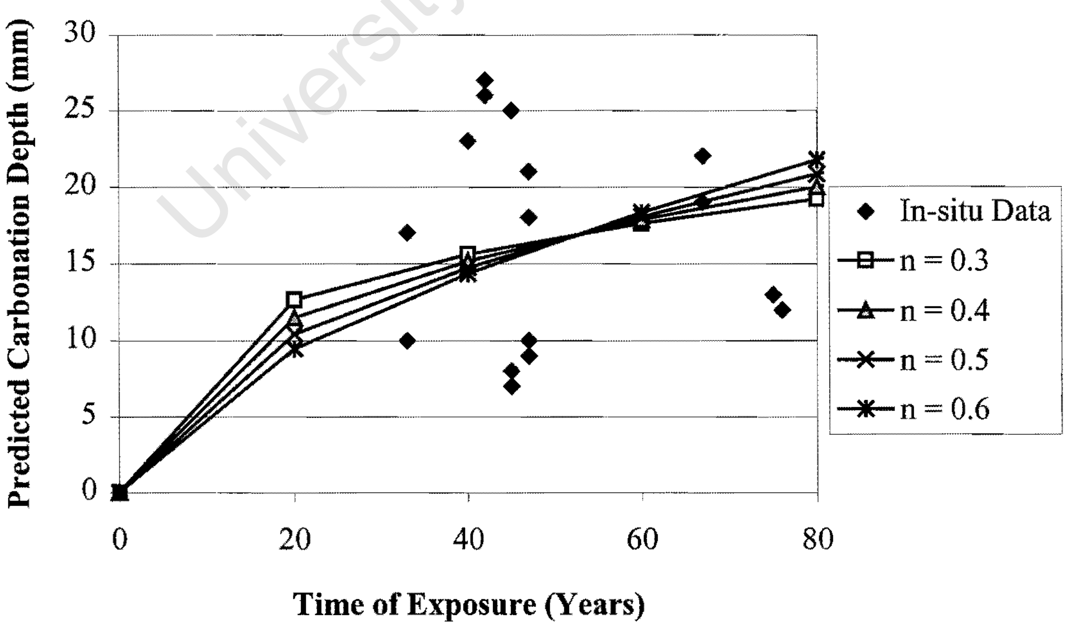


Figure 5.26: Carbonation predictions for different n and k values for exposed Grade 20 concretes in the Cape Peninsula locality

Table 5.15: Values of k and sum of square of residuals (e^2) for fixed n-value for exposed Grade 30 concretes in the Cape Peninsula locality

n	k	e^2
0.3	3.68	620.7
0.4	2.58	585.9
0.5	1.81	559.5
0.6	1.26	541.1

Table 5.16: Predicted depths of carbonation for the chosen n values for exposed Grade 30 concretes in the Cape Peninsula locality

Time, t	Predicted Carbonation Depth, d_c (mm)			
(Years)	n = 0.3	n = 0.4	n = 0.5	n = 0.6
0	0.0	0.0	0.0	0.0
20	9.0	8.6	8.1	7.6
40	11.1	11.3	11.4	11.5
60	12.6	13.3	14.0	14.7
80	13.7	14.9	16.2	17.5
100	14.7	16.3	18.1	20.0

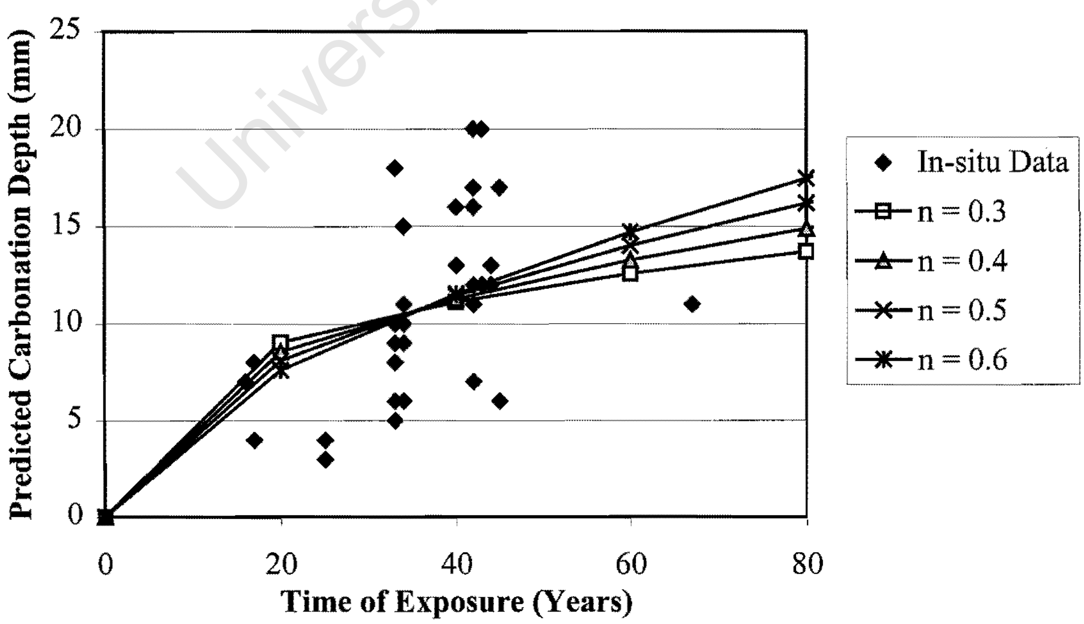


Figure 5.27: Carbonation predictions for different n and k values for exposed Grade 30 concretes in the Cape Peninsula locality

Table 5.17: Values of k and sum of squares of residuals (e^2) for fixed n-value for exposed Grade 40 concretes in the Cape Peninsula locality

n	k	e^2
0.3	2.91	76.6
0.4	2.13	75.6
0.5	1.56	76.8
0.6	1.14	80.2

Note: Regarding the comparison between the sums of square of residuals, they should only be compared when the same number of results are present. If the number of results is not the same, then the model with the greater number of results would have a larger sum of squares of residuals. Therefore, the direct comparison of models with different number of results is meaningless. A special case exists in Grade 40 concrete, the sums of square of residuals for all selected n values are based on the results after the 2nd elimination of outliers whilst ignoring the results after the 3rd gross outlier elimination for n-values equal to 0.3 and 0.4, due to the necessity of comparing the same number of results (see Appendix D).

Table 5.18: Predicted depths of carbonation for the chosen n values for exposed Grade 40 concretes in the Cape Peninsula locality

Time, t	**Predicted Carbonation Depth, d_c (mm)**			
(Years)	**n = 0.3**	**n = 0.4**	**n = 0.5**	**n = 0.6**
0	0.0	0.0	0.0	0.0
20	7.1	7.1	7.0	6.9
40	8.8	9.3	9.9	10.4
60	9.9	11.0	12.1	13.3
80	10.8	12.3	14.0	15.8
100	11.6	13.4	15.6	18.1

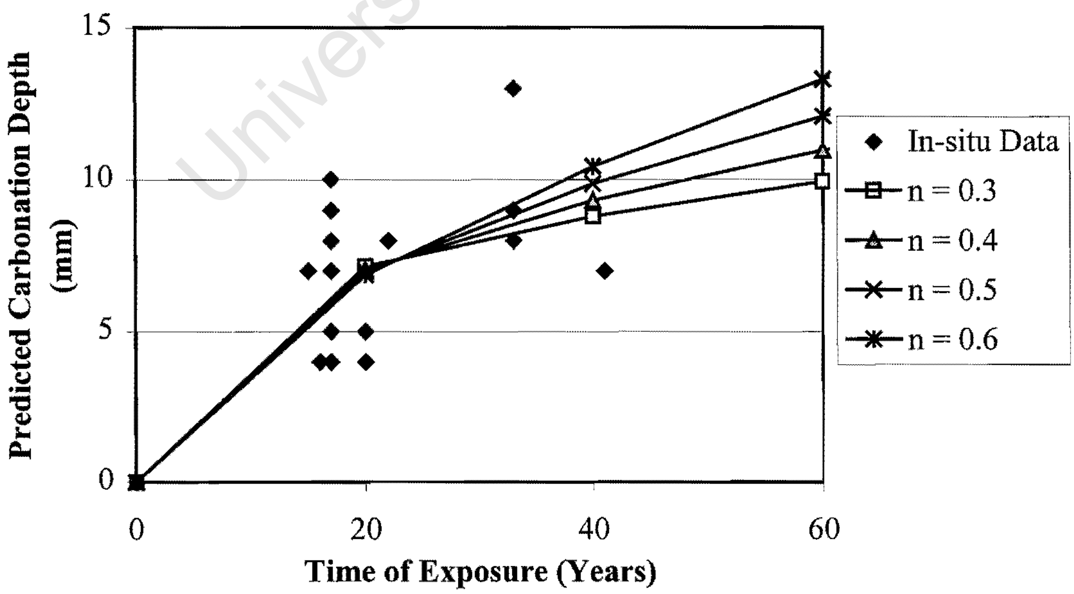


Figure 5.28: Carbonation predictions for different n and k values for exposed Grade 40 concretes in the Cape Peninsula locality

• Comparison and Discussion

Statistically, the sum of squares of residuals can help to decide the values for both k and n values which can represent the best fit to the given carbonation data. The best fit k and n values should be those which give the smallest sum of squares of residuals. However, in the present analysis, the smallest sum of squares of residuals for two concrete grades is given by n equals 0.3 for Grade 20, or 0.6 for Grade 30 concretes, whilst n equals 0.4 for Grade 40 concretes. As explained earlier, according to the law of diffusion the power series constant n should be less than or close to 0.5. Values of n greater than 0.5 are in general difficult to justify unless it is known that the concrete is damaged (due to for example microcracking), while values of n less than 0.4 are in general unrealistic (leading to underestimation) for normal exposed concrete. The results obtained from the present analysis may be attributed to the distribution of data. From Figures 5.26 – 5.28, one can see that all the prediction models with different n and k values "converge" in the middle ('centroid' with respect to time) of the main population group (e.g. between 30 and 60 years exposure in Grade 20 concretes). The residuals of these data within the main population group for each model with different k and n values would be roughly the same. In other words, the major differences in the sum of square of residuals are due to the data which are not within the main population group.

Since the statistical analysis alone cannot provide a reasonable prediction model for each concrete grade, the selection of the prediction model should be based on the understanding of the process of carbonation and a scientific point of view. The concrete elements for each concrete grade are exposed elements. This means these elements would therefore be subject to periodic wetting due to rain. The rate of carbonation decreases when the moisture content of the near-surface concrete is high because diffusion of carbon dioxide through water is very slow, as well as the average relative humidity for high rainfall season (six months a year) is high (see Table 4.4) being above the optimum relative humidity range for carbonation. In addition, the densification of pore structure due to the formation and deposition of calcium carbonate into the concrete pores can slow down the rate of carbonation with time. Therefore, the n value should be lower than that of the theoretical n-value of

0.5. Then a possible n-value could only be 0.4, as the value of 0.3 leads to the underestimation of the depth of carbonation for later ages, although the predicted carbonation depths from n equals to 0.3 and 0.4 do not differ greatly in practical terms. However, based on the understanding of carbonation and conservative purpose for design and construction, n equals to 0.4 would be the most appropriate value to be chosen for each concrete grade. The prediction models for each concrete grade are listed in Table 5.19 and shown graphically in Figure 5.29.

Table 5.19: Prediction models derived by method of least squares

Grade	Carbonation Prediction Model
Grade 20	$d_c = 3.47t^{0.4}$
Grade 30	$d_c = 2.58t^{0.4}$
Grade 40	$d_c = 2.04t^{0.4}$

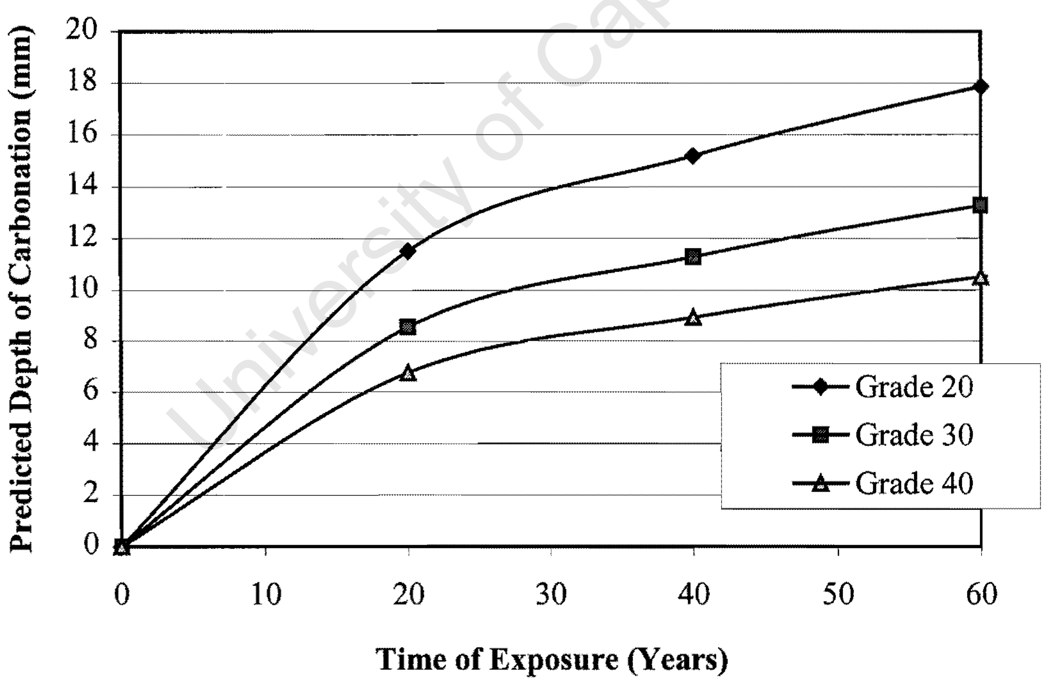


Figure 5.29: Carbonation depth prediction based on method of least squares

The direct comparison of the carbonation coefficient k between these concrete grades is meaningful as the prediction models have the same power series constant n values.

Grade 20 concretes have the highest k value which indicates the rate of carbonation of Grade 20 concrete is the most rapid. The k value for Grade 30 does not differ dramatically from the k value of Grade 40 and hence the depths of carbonation for these two grades of concrete are fairly similar as shown in Figure 5.29. In other words, the rates of carbonation for these two concrete grades are similar. This result is supported by Figure 5.15 (in Neville (1995)) that the permeability (which has a serious effect on the rate of carbonation as explained in section 3.3.2) of these two grades of concretes is similar. It can be seen that the carbonation predictions for Grade 30 and Grade 40 in the present analysis are not as close as in the previous analysis, and this is because the present analysis "force" the n values for both to be equal.

The prediction models derived by the present analysis are considered to be "superior" to the previous analysis. Firstly, it is useful to fix the shape of the curve by selecting an n value based on an understanding of the physics of the problem (in this case, effect of environment on rates of diffusion of carbon dioxide). Secondly, analyses based on power regression have a problem of the assignment of a non-zero "initial" point which has a crucial effect on the values of both k and n which leads to an inaccuracy in both of these values.

The derived models from the method of least squares can be regarded as a "tool" to establish the most appropriate n-value for each concrete grade in the Cape Peninsula locality conditions. For design and construction purposes, a more "conservative" model for each concrete grade should be used. The more "conservative" models refer to the model which predicts, for example, the 80^{th} percentile carbonation depth value. Detailed information in this regard and the computation of different percentile carbonation depth values for each concrete grade will be provided in section 5.6.

5.3 DURBAN LOCALITY

5.3.1 Overview of Field Data

Figure 5.30 shows the overview of the field data obtained for bridges in Durban (Durban – KwaZulu Natal South Coast) locality. This overview is a scatter diagram of all the data without grouping the data. The information on the data such as the name and the year of construction of each bridge, types and designed grades of elements, etc, can be found in section 4.4.2.

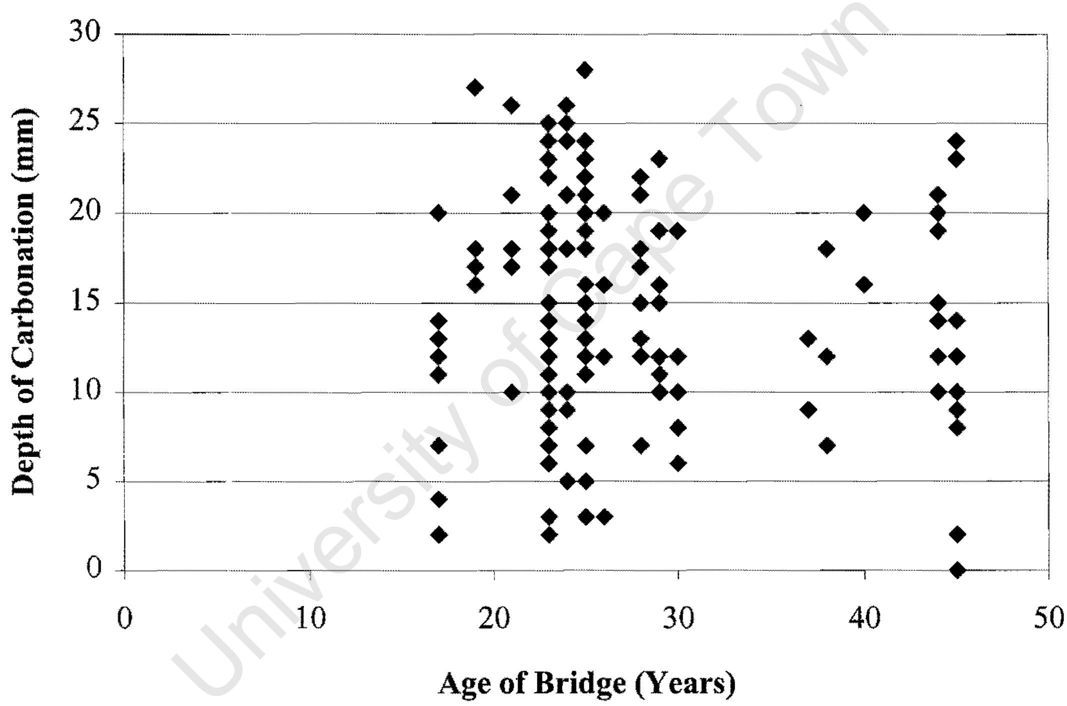


Figure 5.30: Overview of all carbonation data in Durban locality

The carbonation data, as in the Cape Peninsula locality, have a very wide scatter. This wide scatter may in part be due to effects of grade (concrete quality) and exposure conditions on the rate of carbonation. Thus, as in the Cape Peninsula locality, grouping of data in terms of grades and exposure conditions is necessary prior to the analysis of the data. Interestingly, it seems there are two distinct populations with two different rates of carbonation according to Figure 5.30. The first population is aged from 17 to 30 years (1970 – 1982) whilst the second such population is aged from 37 to 45 years (1956 – 1964). Further investigation on this aspect will follow.

5.3.2 Types of Bridges

Results were obtained from three types of bridge. They are road-over-road, road-over-river and footbridge-over-road. The rate of carbonation for these types of bridge does not differ significantly (see Figure 5.31, 5.34 and 5.38 in later sections). Therefore, all types of bridges are analysed together in Durban locality, and using statistics to distinguish any carbonation depth gross outliers.

5.3.3 Determination of Exposure Conditions

As previously defined, exposed elements are those exposed to sun, rain and wind while sheltered elements refer to those sheltered from sun and rain. However, no field trips were possible to examine these bridges, thus the determination of exposure conditions for the elements in this locality is based on the exposure conditions for similar bridge elements for bridges in the Cape Peninsula locality. Generally speaking, exposed elements included balustrades, deck edges, edge columns and wing walls. Sheltered elements were deck soffits, abutments and internal columns.

As pointed out previously, the rate of carbonation between these two exposures may be different, therefore, the elements of these two exposures are analysed separately.

5.3.4 Assessment of Equivalent Compressive Strength at 28 Days

The compressive strengths of the elements were obtained from the original bridge design drawings and were given in Table 4.6. However, the drawings of some bridges were not available and therefore assumed design grades for the elements of those bridges were used. Those bridges were mainly constructed between 1956 and

1964. The concrete grade used in that period for bridge construction, as supported by other bridges constructed in the same period, was approximately Grade 20. Hence, Grade 20 was assumed for those elements without available grade records and marked with an asterisk (*) in the Database provided in Table 4.6.

5.3.5 Grouping of Concrete Grades

The carbonation results were first divided according to their exposures (i.e. exposed or sheltered) and then according to the concrete grades. Three bands of concrete grade were chosen, namely, Grade 20-25, Grade 30-35 and Grade 40-45 based on the distribution of the results as shown below:

Table 5.20: Distribution of carbonation results of Durban locality

Population Group	**Frequency of the Design Concrete Strength Grade (MPa) at 28 Days**					
	Grade 20	Grade 25	Grade 30	Grade 35	Grade 40	Grade 45
1970 – 1982	7	58	29	2	12	2
1956 – 1964	26	0	0	0	2	0

Other grade bands would be unsatisfactory since they would result in either very few or too many data in one particular grade band, and this makes a high degree of statistical unreliability for those grade bands with very few data.

5.3.6 Derivation of Carbonation Prediction Models

As noted previously, there exist two distinct population groups (see Figure 5.30) with different rates of carbonation. The first population group, aged between 17 and 30 years, has a faster carbonation rate than that of the second population group, aged between 37 and 45 years. The difference in the carbonation rate for these two populations manifests more clearly after the carbonation results are grouped according to the corresponding concrete grade band (for example, see Figure 5.31). The reasons for this difference are most likely attributed to the changes in material properties, specifically cement properties over the years. Detailed investigation in this regard is beyond the scope of this research. However, a brief discussion on this issue will be provided later. Therefore, it is advisable to analyse these two populations separately. The rate of carbonation for the first population would be underestimated and the rate of carbonation for the second population would be overstated if analysing the two populations together.

As pointed out in the previous section, the assignment of the "initial" point and the lack of and the inclusion of early age data can affect the carbonation prediction model derived by power regression (Excel). In the present locality, only the use of Method of Least Squares will be employed in order to select the most suitable power series constant n.

As also pointed out in the previous section, based on diffusion theory as well as the understanding of carbonation of concrete, this n value should either be close to 0.4 or 0.5, and only one decimal place is chosen in the analysis for simplicity.

The analytical procedures for analysing the carbonation results for this locality including the detection of carbonation depth gross outliers are identical to those for the analysis in the Cape Peninsula locality, and are provided in Appendix E. Only the key analytical results for each concrete grade band under each exposure will be shown below followed by discussion.

(a) Exposed Elements

• Grade 20-25

Table 5.21: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 20-25 concretes in Durban locality

Population	**1970 - 1982**		**1956 - 1964**	
n	**k**	**e^2**	**k**	**e^2**
0.4	4.93	1317.5	3.08	351.1
0.5	3.57	1364.8	2.12	352.5

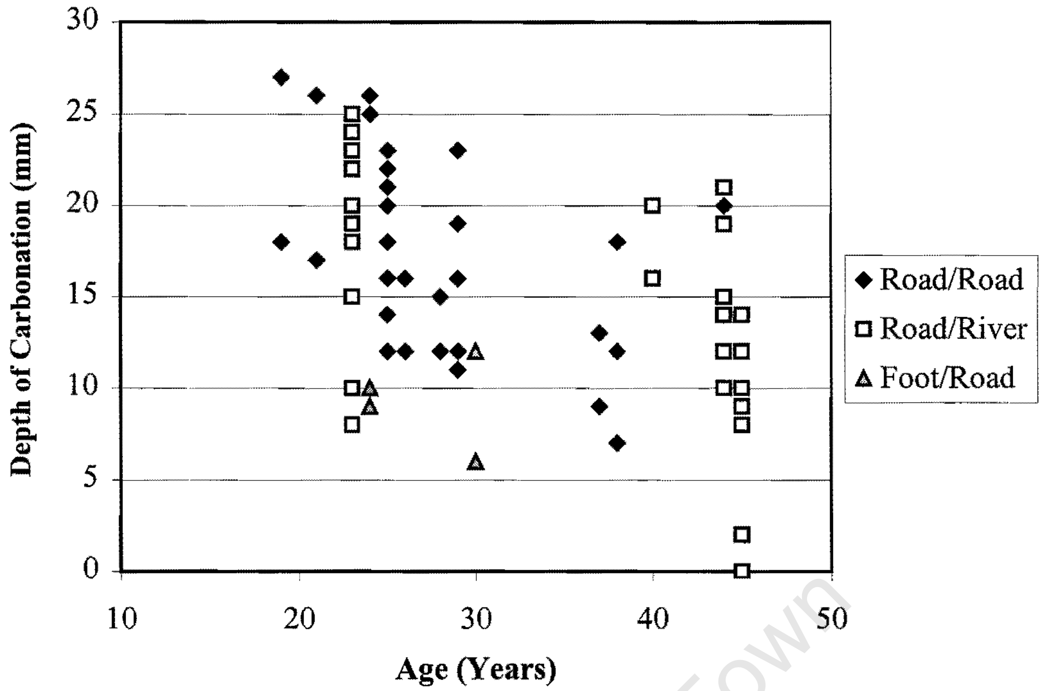


Figure 5.31: Carbonation results for exposed Grade 20-25 elements in Durban locality (all results)

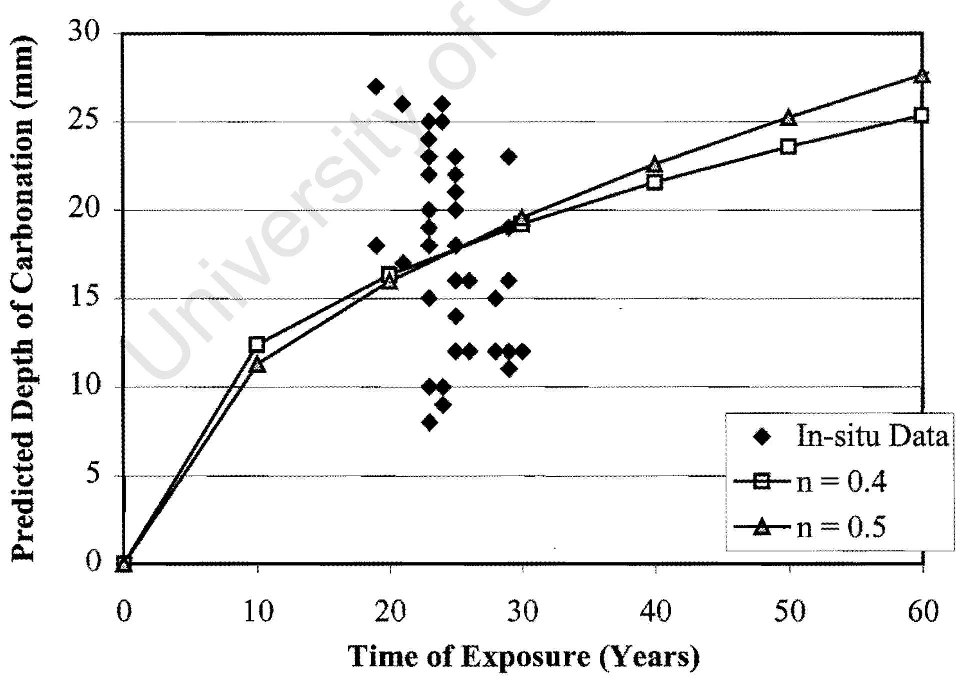


Figure 5.32: Carbonation predictions for different n values and the field carbonation results (without gross outliers, 1 No.) for exposed Grade 20-25 concretes between 1970 and 1982 in Durban locality

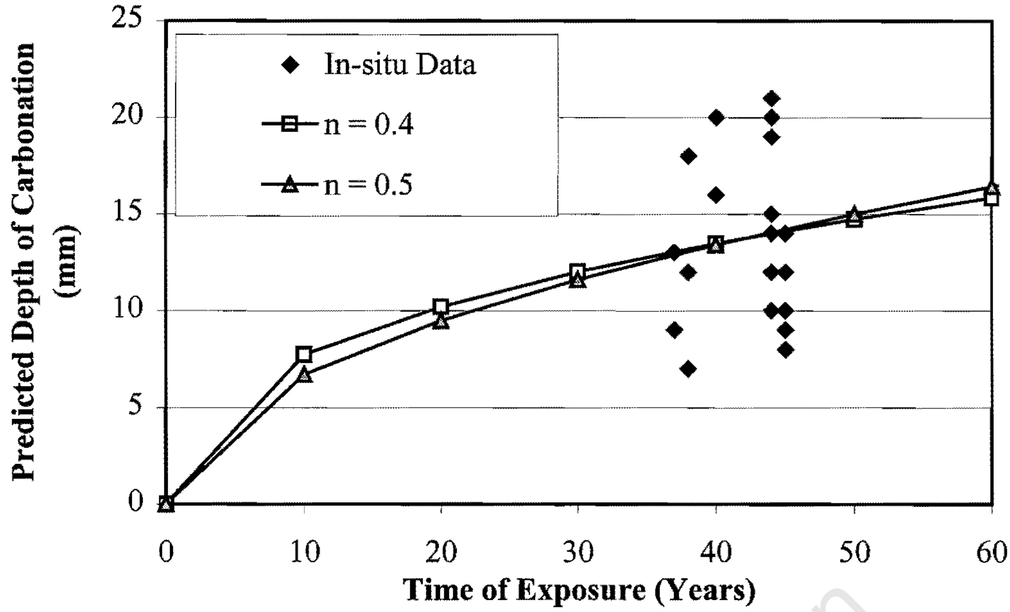


Figure 5.33: Carbonation predictions for different n values and the field carbonation results (without gross outliers, 2 No.) for exposed Grade 20-25 concretes between 1956 and 1964 in Durban locality

- Grade 30-35

Only the first population (1970 – 1982) is considered for this concrete grade band as no carbonation results obtained were from the second population group (1956 – 1964).

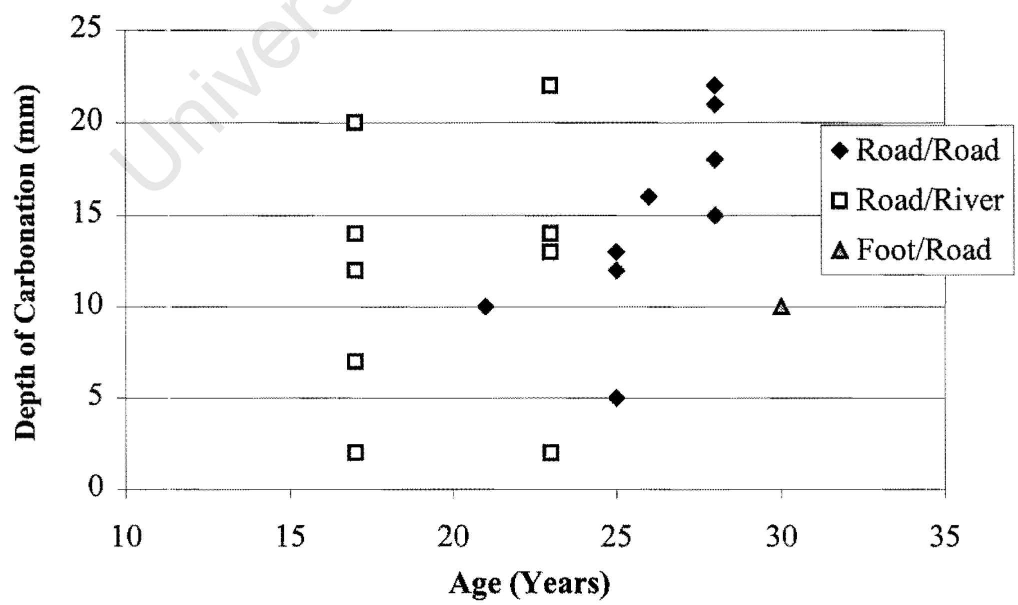


Figure 5.34: Carbonation results for exposed Grade 30-35 elements in Durban locality (all results)

Table 5.22: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 30-35 concretes in Durban locality

n	k	e^2
0.4	3.75	624.9
0.5	2.74	618.1

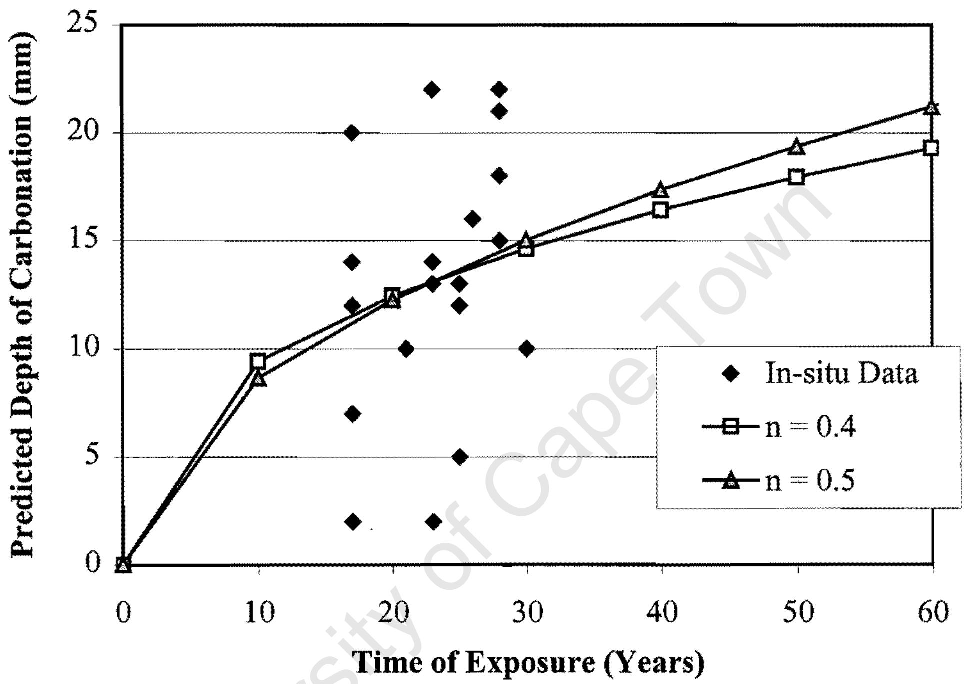


Figure 5.35: Carbonation predictions for different n values and field carbonation results (no gross outliers found) for exposed Grade 30-35 concretes between 1970 and 1982 in Durban locality

- Grade 40-45

There were only three carbonation results in the 1970 –1982 population group and only two results in 1956 – 1964 population group, thus no analysis was carried out for this concrete grade band.

• Comparison and Discussion

Exposed Grade 20-25 concretes have a smaller sum of squares of residuals (e^2) for both populations when n equals 0.4 (see Table 5.21). This implies an n value of 0.4 fits the carbonation results better and therefore this n value is more appropriate for this concrete grade band than the "theoretical" n value of 0.5.

The 1970 – 1982 population has a faster rate of carbonation than that of the 1956 – 1964 population as can be seen by comparing the k values for the two populations when n equals the appropriate value of 0.4 (see Table 5.21). Figure 5.36 illustrates the difference in rates of carbonation between these two populations graphically:

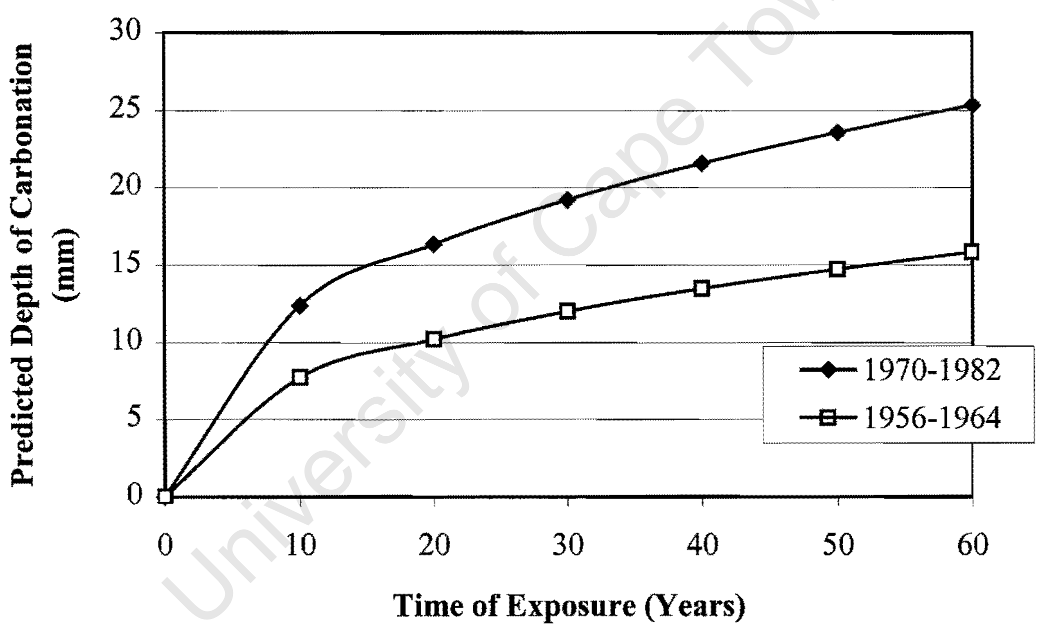


Figure 5.36: The difference in rates of carbonation for exposed Grade 20-25 concretes for the two populations in Durban locality

The initial visual judgment of two distinct populations (with two distinct rates of carbonation) for this grade band of concrete in the present locality is supported by the statistical analysis as shown above. The difference in carbonation rates between these two populations is substantial, showing that it is sensible to analyse these two populations separately in order to avoid the establishment of a misleading (either overstated or underestimated) prediction model as explained earlier. In simple terms, this difference suggests that the "older" concretes have a slower rate of carbonation than "younger" concretes of the same grade when exposed to the environment of the present locality. The possible reasons as well as the implications associated with this different carbonation rate will be discussed later.

For exposed Grade 30-35 concretes, although the sum of squares of residuals (e^2) when n equals 0.4 is slightly larger than that of 0.5, the value of 0.4 is still more appropriate owing to the effects of periodic wetting, and the average relative humidity for "wet" season (seven months a year) being above the optimum range for carbonation (see Table 4.4), as well as the process of carbonation can refine the pore structure and hence slows down the rate of carbonation. Nevertheless, the e^2 for these two n values only differs by 0.88%.

By comparing the predicted depths of carbonation between Grade 20-25 and Grade 30-35, one can see that the material factor of concrete does have an effect on the rate of carbonation as follows:

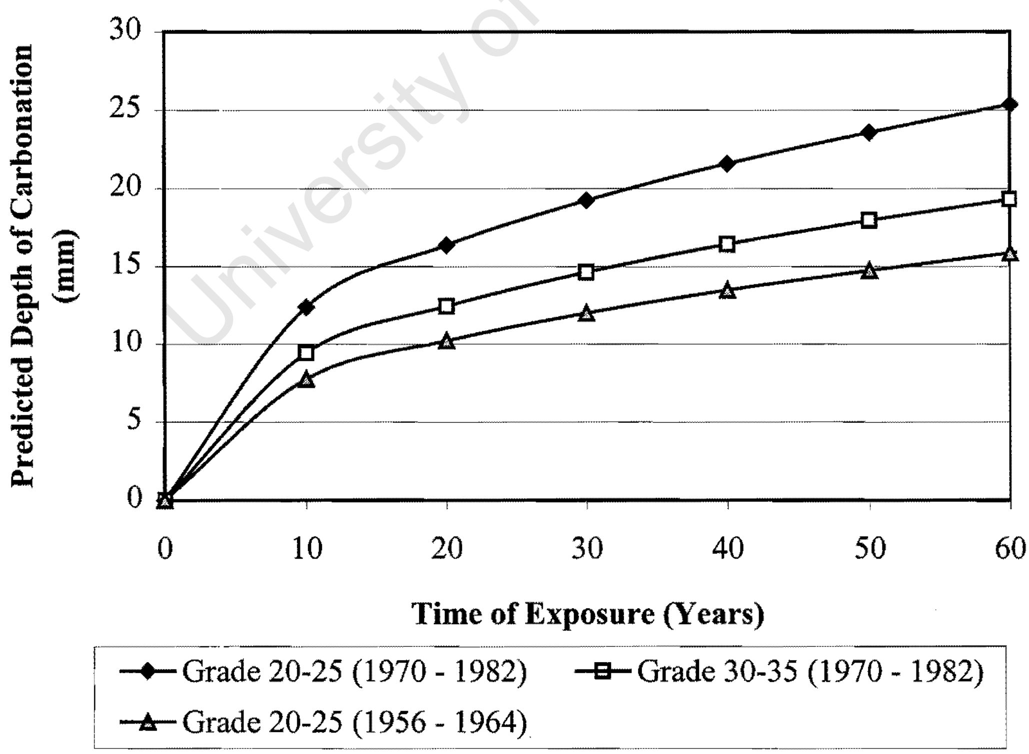


Figure 5.37: Carbonation prediction for exposed concretes for the two populations in Durban locality

Table 5.23: Summary for the prediction models for different exposed concrete grade bands in Durban locality

Grade Band	Carbonation Prediction Model
20 – 25 (1970 – 1982)	$4.93t^{0.4}$
20 –25 (1956 – 1964)	$3.08t^{0.4}$
30 – 35 (1970 – 1982)	$3.75t^{0.4}$

Note: The analysis of exposed Grade 30-35 (1956 – 1964), Grade 40-45 (1970 – 1982) and Grade 40-45 (1956 – 1964) have not been carried out due to insufficient data

As expected Grade 20-25 concretes have a higher carbonation rate than Grade 30-35 in the 1970 – 1982 population group, because of the fact that the former concrete grade band is more permeable than the latter because it has a higher water/cement ratio, provided other factors such as degree of compaction and curing are the same. Direct comparison of Grade 20-25 (1956 – 1964) concretes with Grade 30-35 (1970 – 1982) is not practical as they represent different material conditions.

(b) Sheltered Elements

• Grade 20-25

Table 5.24: Values of k and sum of squares of residuals (e^2) for fixed n-values for sheltered Grade 20-25 concretes in Durban locality

Population	1970 - 1982		1956 - 1964	
n	**k**	**e^2**	**k**	**e^2**
0.4	4.82	870.9	3.04	139.4
0.5	3.48	900.4	2.09	142.1

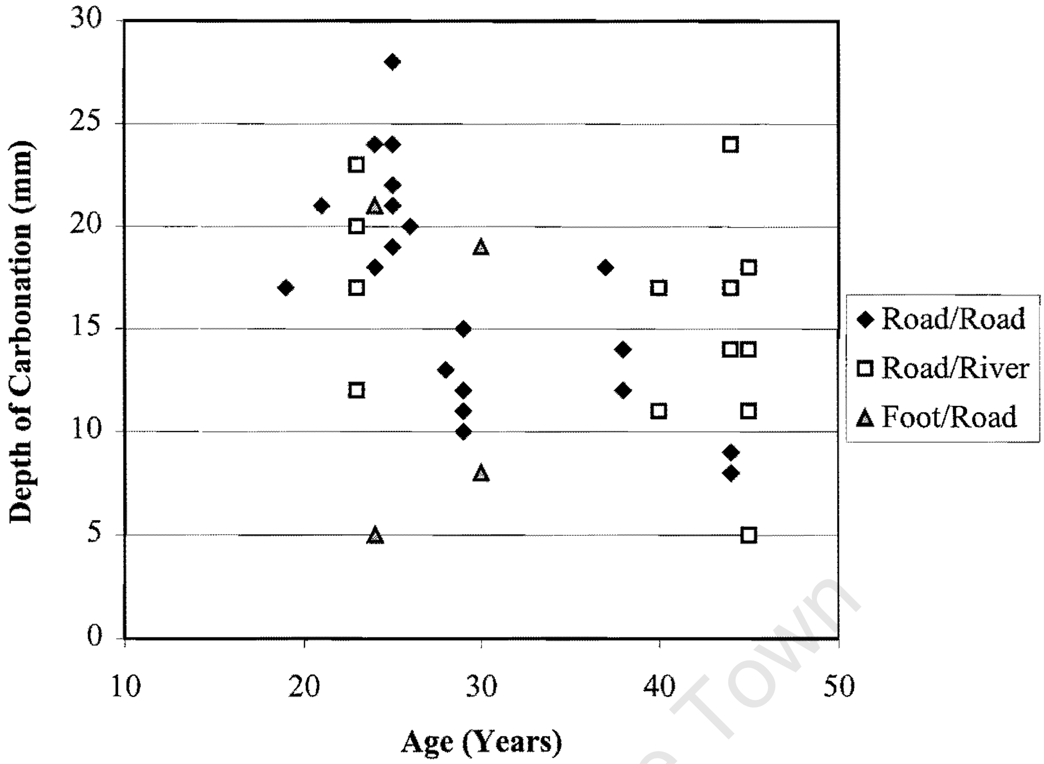


Figure 5.38: Carbonation results for sheltered Grade 20-25 concretes in Durban locality (all results)

Two distinct population groups, namely, 1970 – 1982 and 1956 – 1964 can also be identified from Figure 5.38 above. Separate analysis of the carbonation results of these two population groups was carried out and the analytical results are shown in Figure 5.39 and 5.40. This represents the same situation as for exposed Grade 20-25 concretes. The first population (1970 – 1982) has a faster carbonation rate than that of the second population group (1956 – 1964) as can be seen in Figure 5.41 (the n value of 0.4 can be regarded as the suitable power series constant as it yields the smaller e^2 as shown in Table 5.24 above).

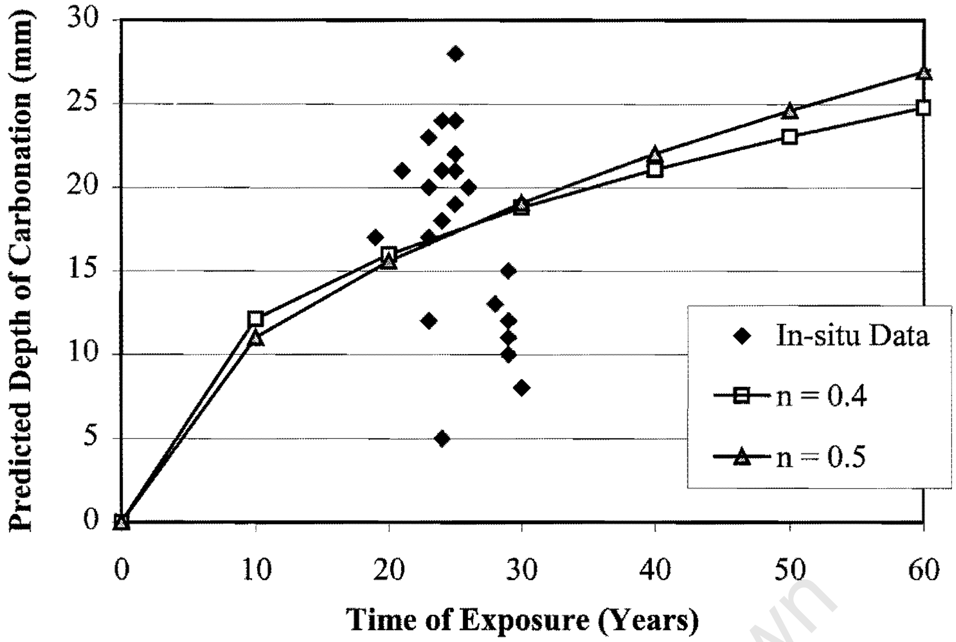


Figure 5.39: Carbonation predictions for different n values and the field carbonation results (no gross outliers detected) for sheltered Grade 20-25 concretes between 1970 and 1982 in Durban locality

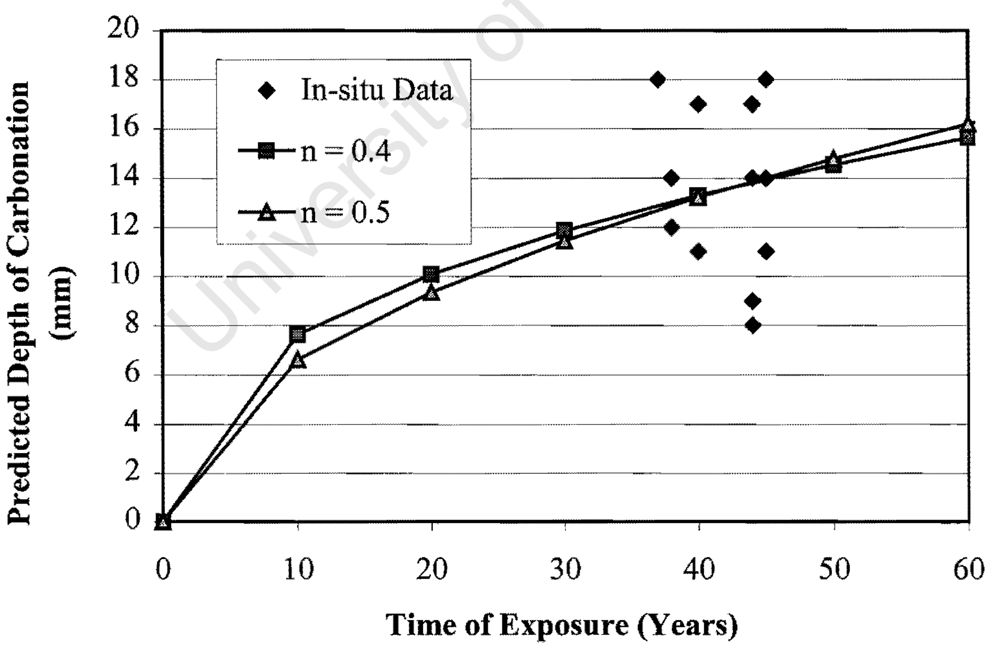


Figure 5.40: Carbonation predictions for different n values and the field carbonation results (without gross outliers, 2 No.) for sheltered Grade 20-25 concretes between 1956 and 1964 in Durban locality

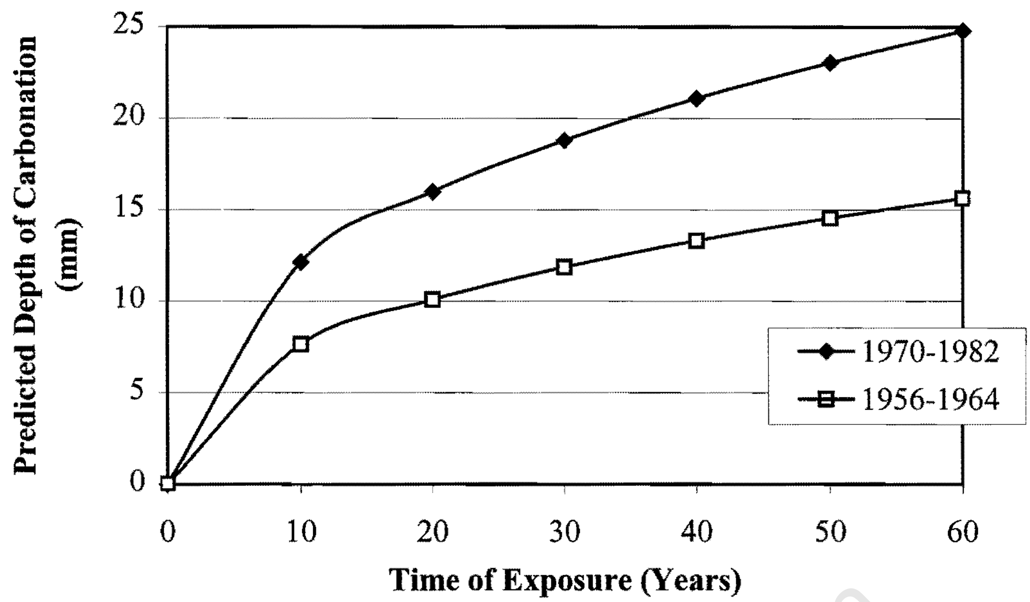


Figure 5.41: The difference in rates of carbonation for sheltered Grade 20-25 concretes for the two populations in Durban locality

- Grade 30-35

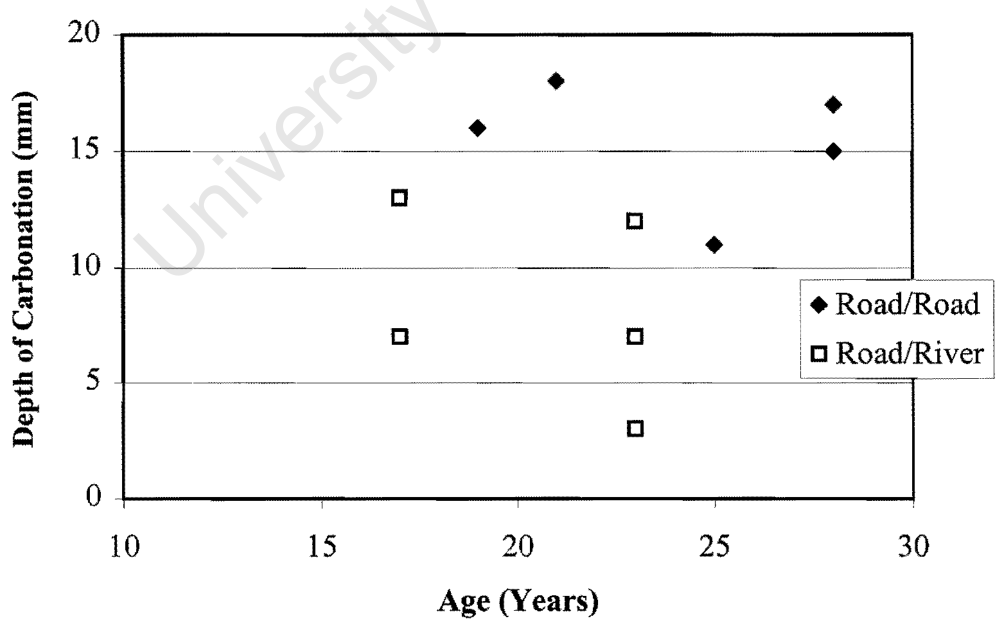


Figure 5.42: Carbonation results for sheltered Grade 30-35 concretes in Durban locality (all results)

Table 5.25: Values of k and sum of squares of residuals (e^2) for fixed n-values for sheltered Grade 30-35 concretes between 1970 and 1982 in Durban locality

n	k	e^2
0.4	3.44	212.1
0.5	2.52	212.3

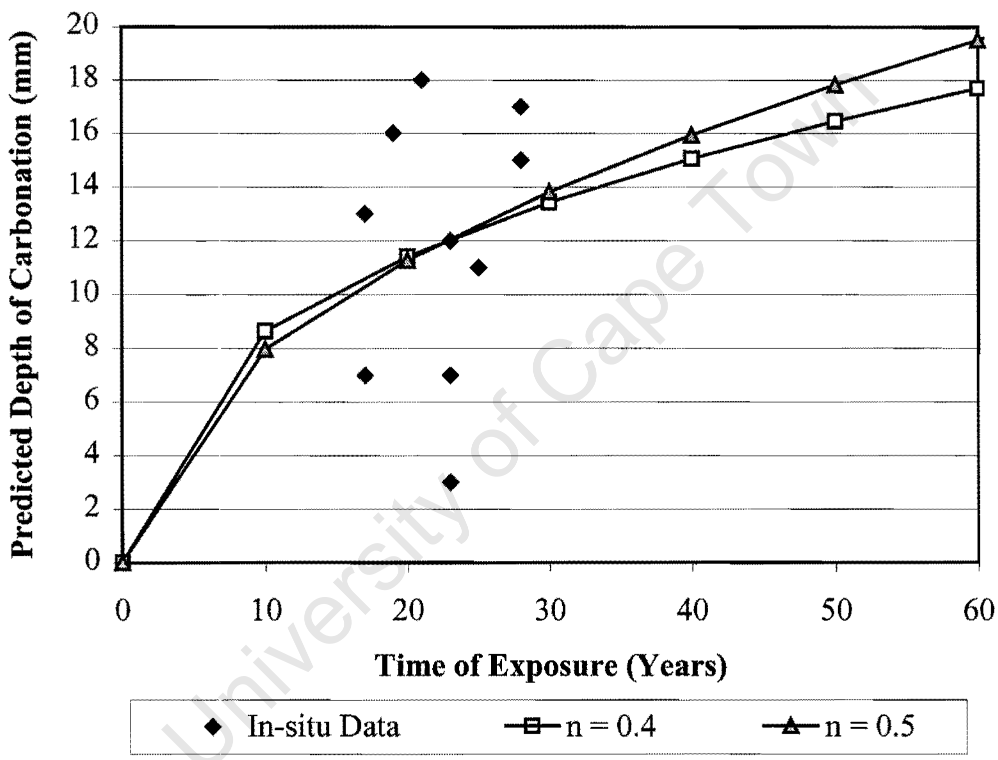


Figure 5.43: Carbonation predictions for different n values and the field carbonation results (no gross outliers detected) for sheltered Grade 30-35 concretes between 1970 and 1982 in Durban locality

• Grade 40-45

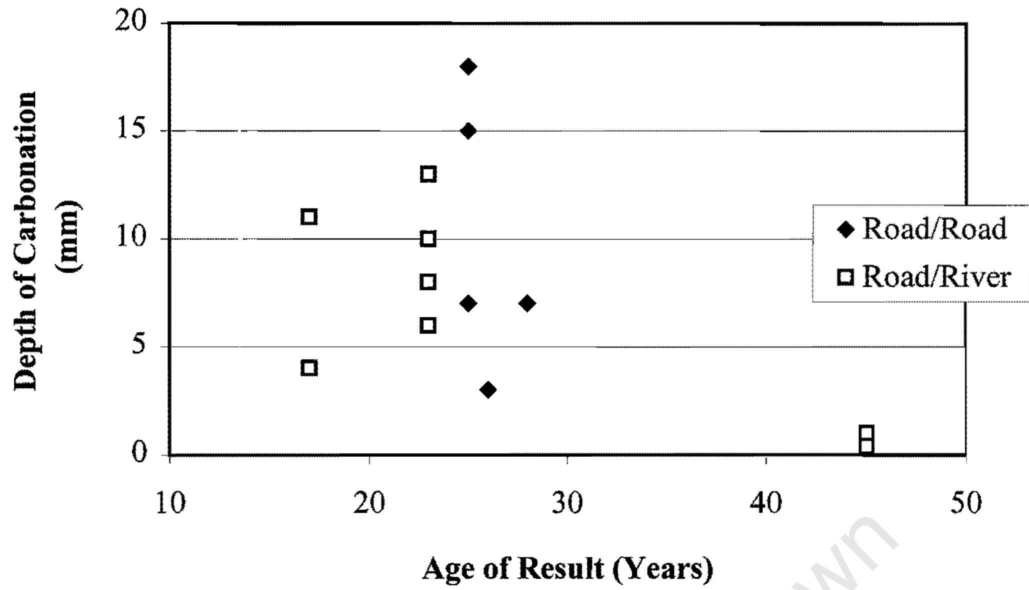


Figure 5.44: Carbonation results for sheltered Grade 40-45 concretes in Durban locality (all results)

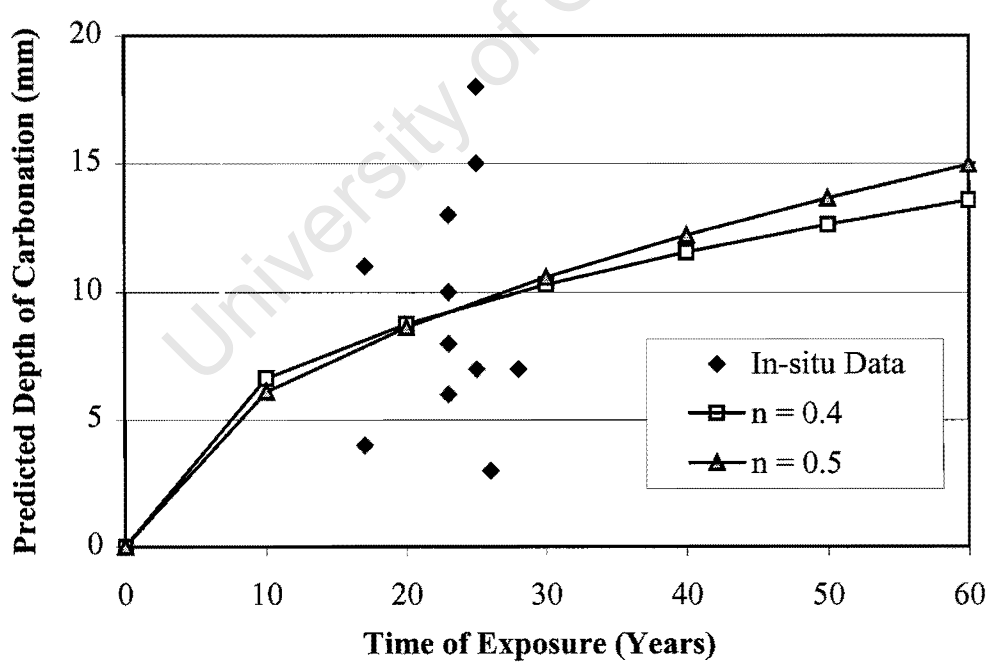


Figure 5.45: Carbonation predictions for different n values and the field carbonation results (without gross outliers) for sheltered Grade 40-45 concretes between 1970 and 1982 in Durban locality

Table 5.26: Values of k and sum of squares of residuals (e^2) for fixed n-values for sheltered Grade 40-45 concretes between 1970 and 1982 in Durban locality

n	k	e^2
0.4	2.64	213.6
0.5	1.93	214.2

• Comparison and Discussion

The value of n equals 0.4 can be regarded as suitable for the sheltered elements in both the period of 1970 – 1982 and 1956 - 1964 and for the grade bands under the present study. The material effects on the rate of carbonation can be seen as shown in Table 5.27 and Figure 5.46.

Table 5.27: Prediction models for different sheltered concrete grade bands in Durban locality

Grade Band	Carbonation Prediction Model
20-25 (1956 – 1964)	$3.04\ t^{0.4}$
20-25 (1970 – 1982)	$4.82\ t^{0.4}$
30-35 (1970 – 1982)	$3.44\ t^{0.4}$
40-45 (1970 – 1982)	$2.64\ t^{0.4}$

It is useful to compare the rate of carbonation between exposed and sheltered elements of the same grade band in the same population (i.e. year of construction) in order to differentiate the effect of exposed and sheltered from the weather (i.e. sun, rain and wind). Figures 5.47 – 5.49 show such comparisons.

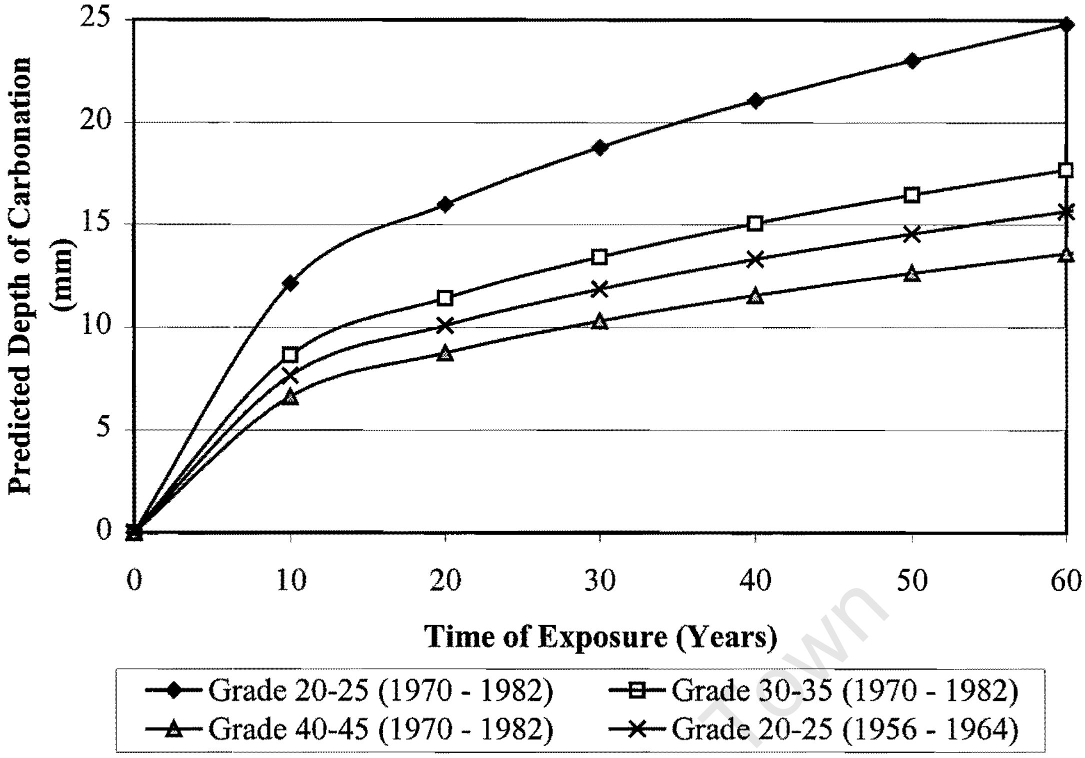


Figure 5.46: Carbonation prediction for sheltered concretes in the Durban locality

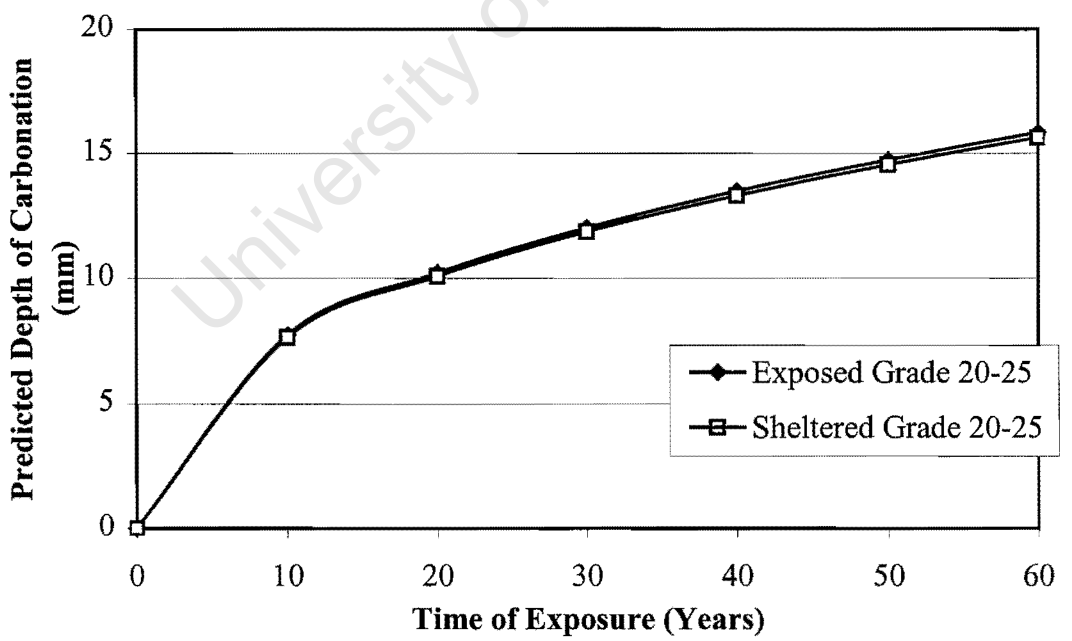


Figure 5.47: Carbonation prediction for exposed and sheltered Grade 20-25 concretes between 1956 and 1964 in Durban locality

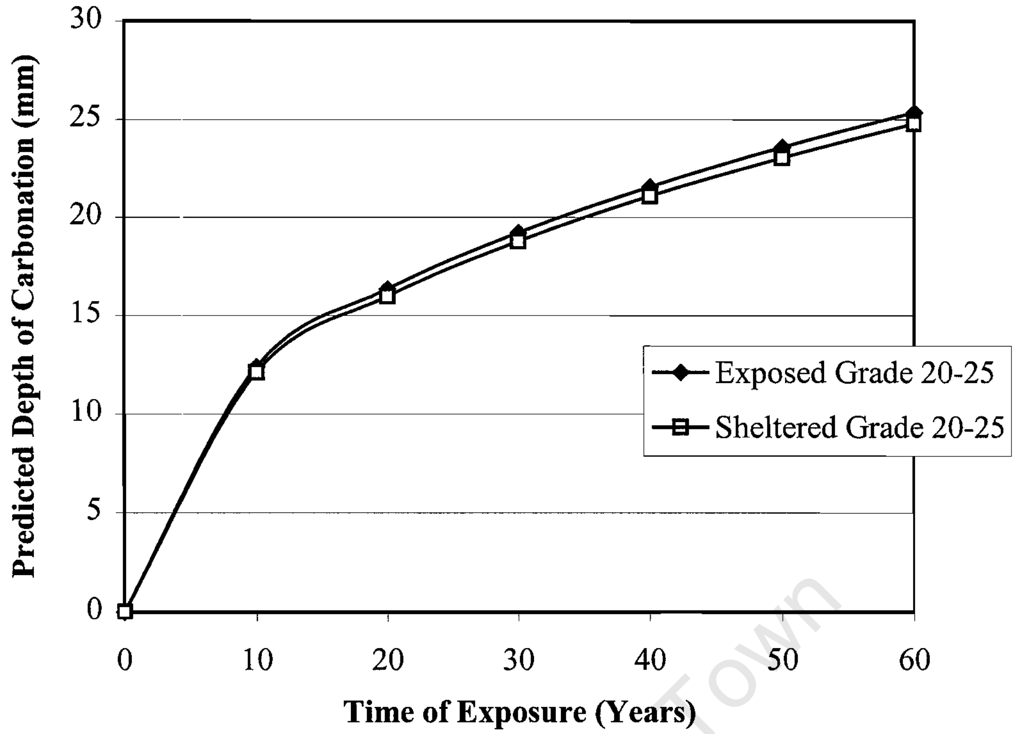


Figure 5.48: Carbonation prediction for exposed and sheltered Grade 20-25 concretes between 1970 and 1982 in Durban locality

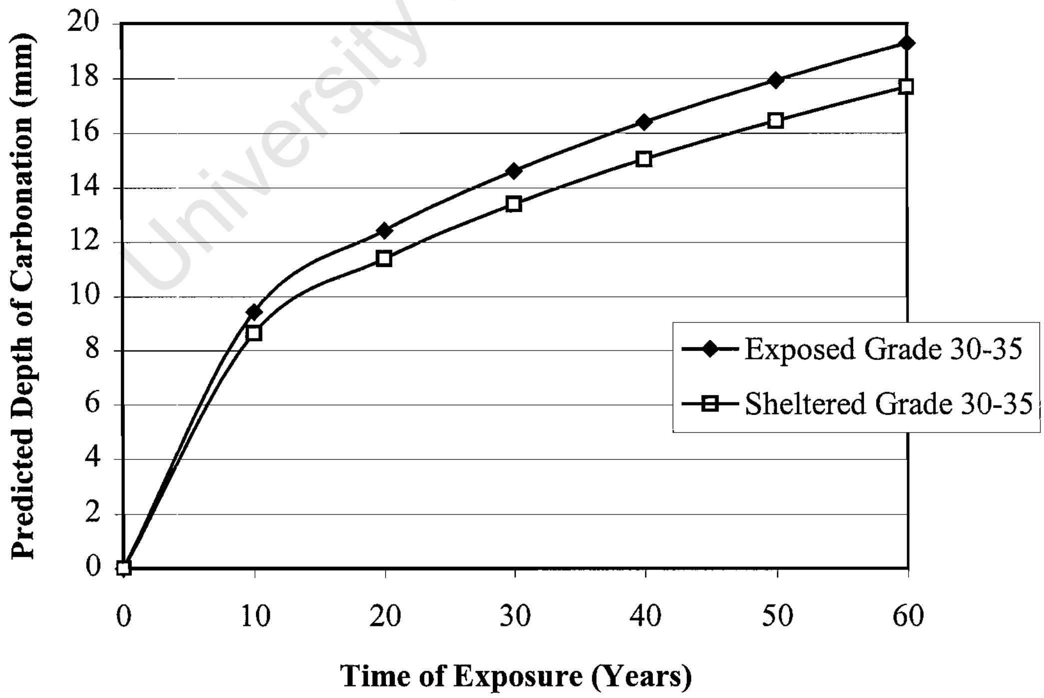


Figure 5.49: Carbonation prediction for exposed and sheltered Grade 30-35 concretes in Durban locality

At the start of this section, it appeared that, by looking at the carbonation results, there were two populations (1970 – 1982 and 1956 – 1964) with different carbonation rates in this locality. Eventually, this "apparent judgement" was supported by the statistical analysis as shown above. Since the carbonation results from these two populations were measured on bridges which were exposed to similar environmental conditions, the possible reasons for the difference in carbonation rates for these two populations must therefore be due substantially to material factors. The factors of local climatic differences between these bridges may also have an effect, but there is no reliable information on these local climatic differences, thus this factor will not be considered here. Materials factors can be focused mainly on cement as other concrete constituents (such as aggregates and mixing water) should have the same properties throughout the years concerned. Since the investigation of the change in properties of South African cements is beyond the scope of this research, only brief discussion in this aspect is provided below.

Fulton (1977) reported that a change of South African ordinary Portland cement. The ordinary Portland cements produced in that period (1970s) tended to comply with the requirements of SABS 471 in respect of rapid-hardening cements. That is to say there was an increase in the tricalcium silicate content (C_3S) while the content of dicalcium silicate (C_2S) was reduced correspondingly. Apart from that, the fineness of ordinary Portland cements has also been increased. The need for these changes is to increase the rate of development of early strengths, due to the demand of high-speed construction from the industry for the purpose of achieving better economic benefits by the early removal of formwork. The results of these changes in cement would increase the heat of hydration and hence the concrete subjected to high thermal contraction and high drying shrinkage as reported by Mehta (2002), and the possibility of micro-cracks being formed. Interconnections of these micro-cracks and voids in concrete form channels for carbon dioxide to penetrate into the concrete. In addition, these changes lead to a higher water/cement ratio to achieve the same compressive strength than that of the "older" cements as illustrated in Figure 5.50 (Alexander (1995). Hence, the rate of carbonation is likely to be faster in the bridges in the population group with a younger age, which presumably is made from finer cement with higher C_3S content, based on the comparisons of carbonation rates between these two population groups in Table 5.28.

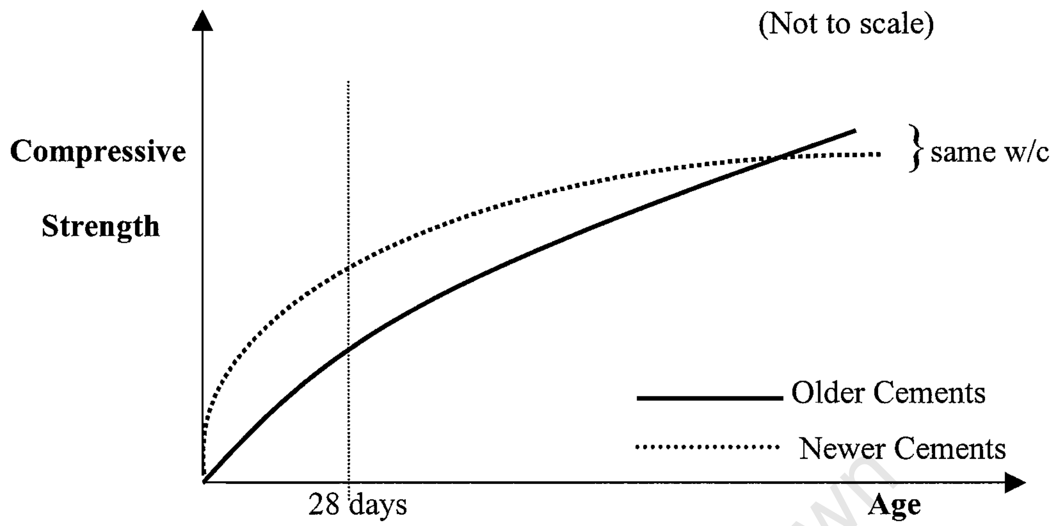


Figure 5.50: Schematic of historical change in cements (Alexander (1995))

Table 5.28: Summary of the prediction models for Durban locality

Exposures to sun, rain and wind	Grade Band	Prediction Model
Exposed	20 – 25 (1956 – 1964)	$3.08t^{0.4}$
	20 – 25 (1970 – 1982)	$4.93t^{0.4}$
	30 – 35 (1970 – 1982)	$3.75t^{0.4}$
Sheltered	20 – 25 (1956 – 1964)	$3.04t^{0.4}$
	20 – 25 (1970 – 1982)	$4.82t^{0.4}$
	30 – 35 (1970 – 1982)	$3.44t^{0.4}$
	40 – 45 (1970 – 1982)	$2.64t^{0.4}$

In this locality, there is another interesting issue to consider which is the carbonation rates for exposed elements and sheltered elements. The carbonation rates between exposed and sheltered elements do not have much practical difference. However, it is reasonable for exposed elements to have a lower rate of carbonation than sheltered elements since exposed elements would be wetted by rain. Hence the moisture content of the near surface pores is too high for rapid diffusion of carbon dioxide. The question arises as to why the analysis shows that there is no practical difference in carbonation rates between exposed and sheltered elements. This is possibly because the relative humidity for high rainfall season in this locality is high (about 79%, see Table 4.4). In this high relative humidity, the moisture content of the near surface is also high even in elements sheltered from direct rain. In addition, the form of rain in this locality is in the form of instability showers (see section 4.3.2) which are of short duration, and the exposed elements return to equilibrium with the relative humidity of about 79% within a short period of time after the showers. Therefore, it may be deduced that the relative humidity of the pores of exposed elements are also presumably close to 79% most of time even in the high rainfall season. In low rainfall season, the effect of rain on the moisture content of the near surface pores of the exposed concrete is less, therefore the relative humidity of the near surface pores for both exposed and sheltered elements should be more or less the same. Thus, the rates of carbonation for these two types of element in the present locality should be similar.

The results suggest that for the computation of different percentile carbonation depth values, the exposed and sheltered elements can be grouped together in order to get a more confident prediction model (as the number of data increased).

5.4 JOHANNESBURG LOCALITY

5.4.1 Overview of Field Data

The detailed information for the carbonation data can be found in section 4.4.3 and the overview of all data is provided in Figure 5.51. The wide scatter for the data is again due to the fact that these data represent different material, construction and exposure conditions. These data will therefore be grouped in different categories similar to the two localities discussed previously, prior to statistical analysis.

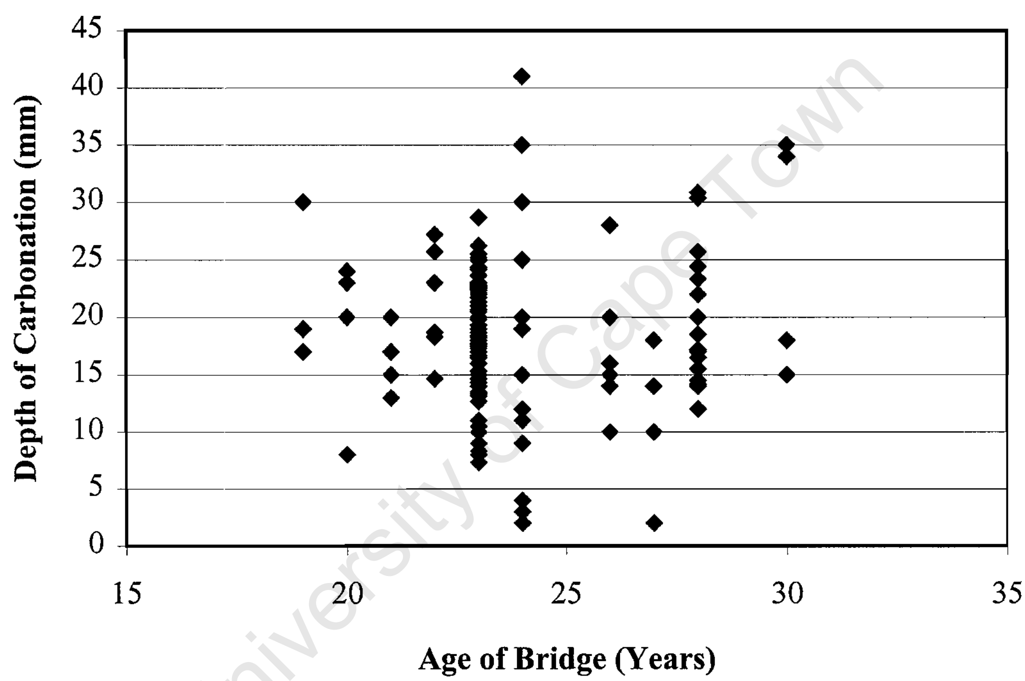


Figure 5.51: Overview of all carbonation data in Johannesburg locality

5.4.2 Types of Bridges

Carbonation data were measured on three types of bridges: road-over-road, road-over-rail and road-over-river. The majority of these bridges was road-over-road. This can be seen from Figure 5.58. These three types of bridges are analysed together as they do not differ remarkably from the findings of previously localities.

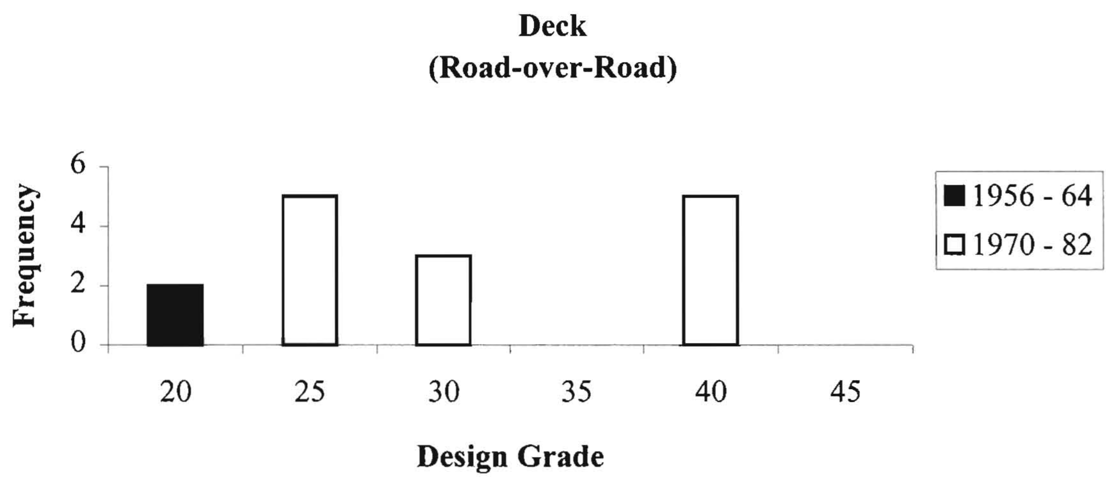
5.4.3 Determination of Exposure Conditions

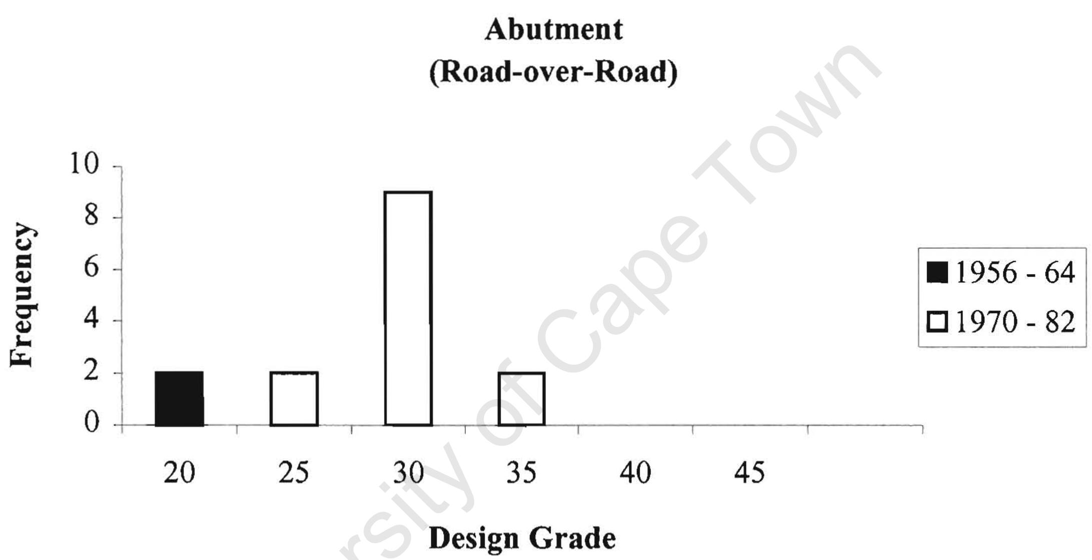
The exposure conditions for the structural elements of the motorway system of the Greater Johannesburg system were described by Ballim and Lampacher (1996), therefore no assumptions on this aspect need to be made. On the other hand, the exposure conditions for the elements of the N3 bridges between the Heidelberg Road and Geldenhuis Interchanges were not available, and therefore assumptions made in this regard are the same as the assumed exposure conditions for the bridge elements in the Durban locality. The assumptions are: edge columns, parapets, wing walls and guard rails are exposed elements whilst deck soffits, abutments and internal columns are sheltered elements.

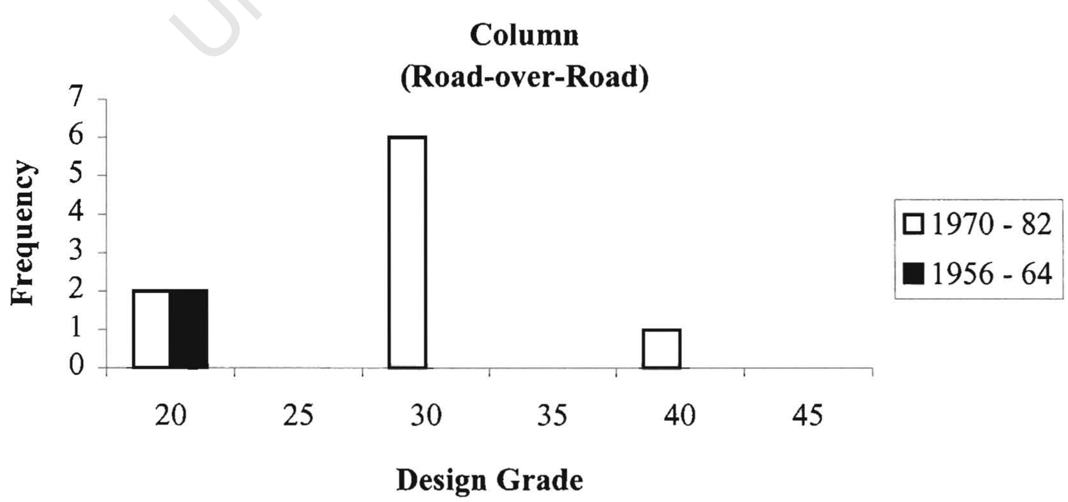
5.4.4 Assessment of Equivalent Compressive Strength at 28 Days

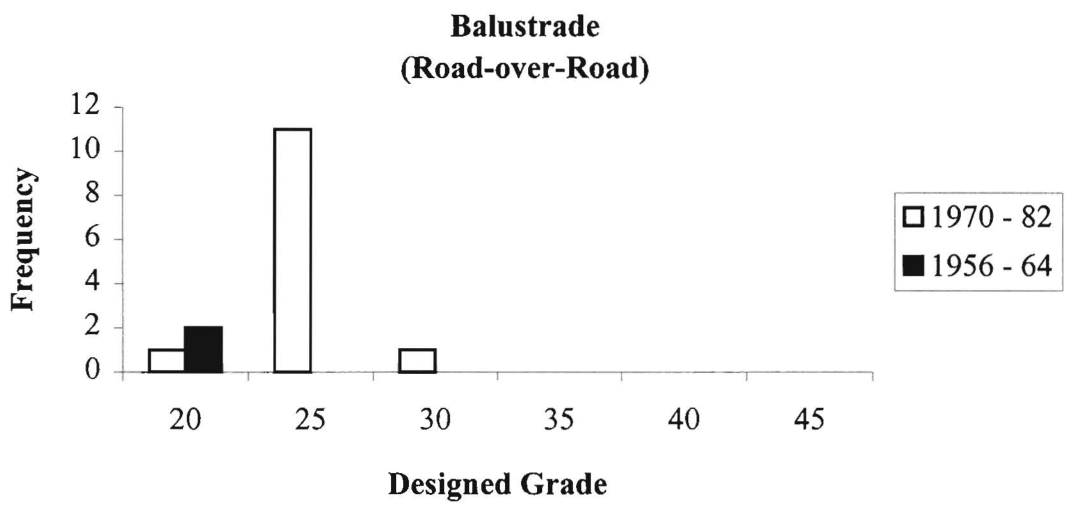
Since no cores were taken from the bridges for compression test in this locality, no measured compressive strengths were obtained. In addition, the design bridge drawings were not available, and thus the specified design concrete strength grade for each element of each bridge was unknown. Ballim and Lampacher (1996) only stated that the columns sampled in the motorway system of the Greater Johannesburg area had a design concrete grade between 20 and 40 MPa and there is no information in this regard for the carbonation data along the N3 freeway.

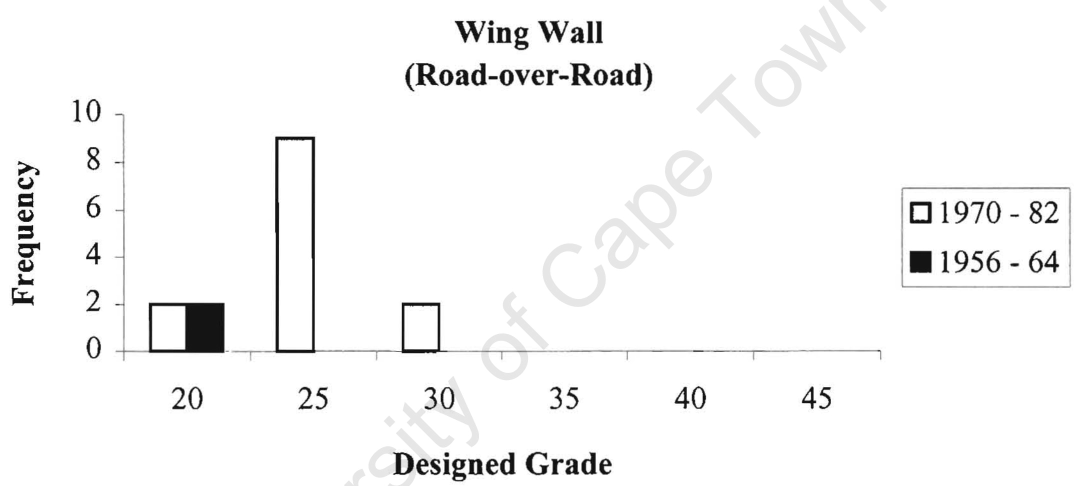
An assumed grade for each element in the present locality would be based on the design grade specified for the bridges in the Durban locality. This was done because the bridges in the present locality as well as the bridges in the Durban locality were constructed in the same period. An analysis of the design grade for different elements of bridges in Durban locality was carried out and the results are shown in Figure 5.52.

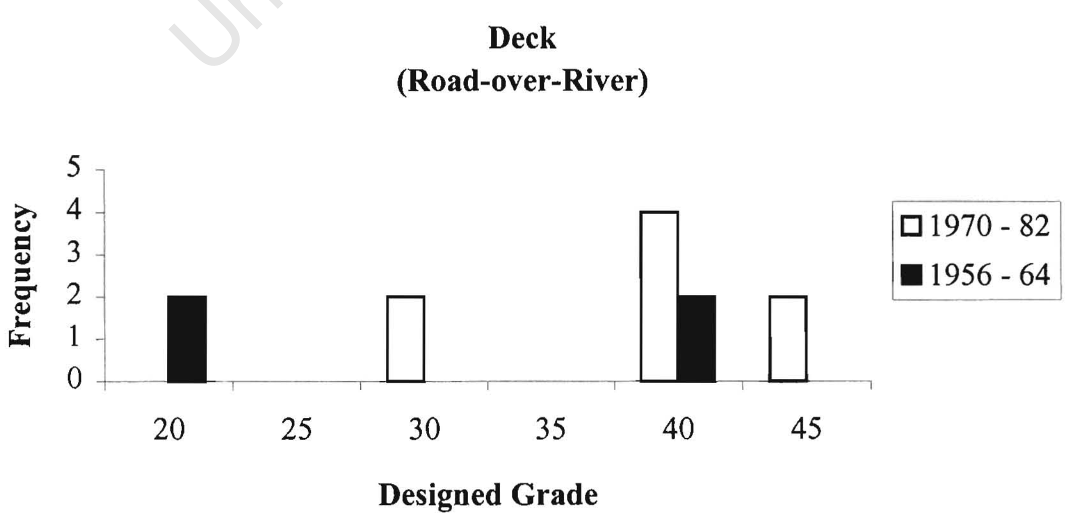

Deck
(Road-over-Road)
Frequency
6
4
2
0
20
25
30
35
40
45
Design Grade
1956 - 64
1970 - 82

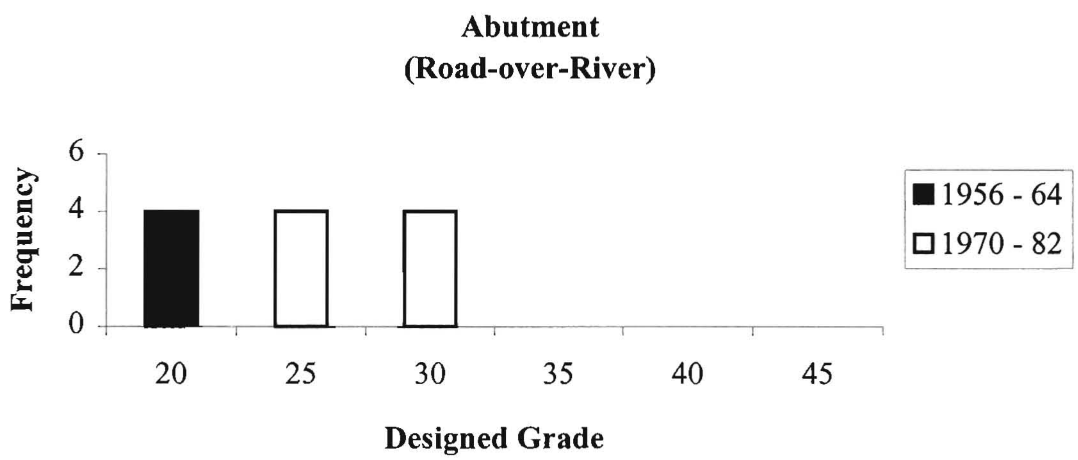

Abutment
(Road-over-Road)
Frequency
10
8
6
4
2
0
20
25
30
35
40
45
Design Grade
1956 - 64
1970 - 82

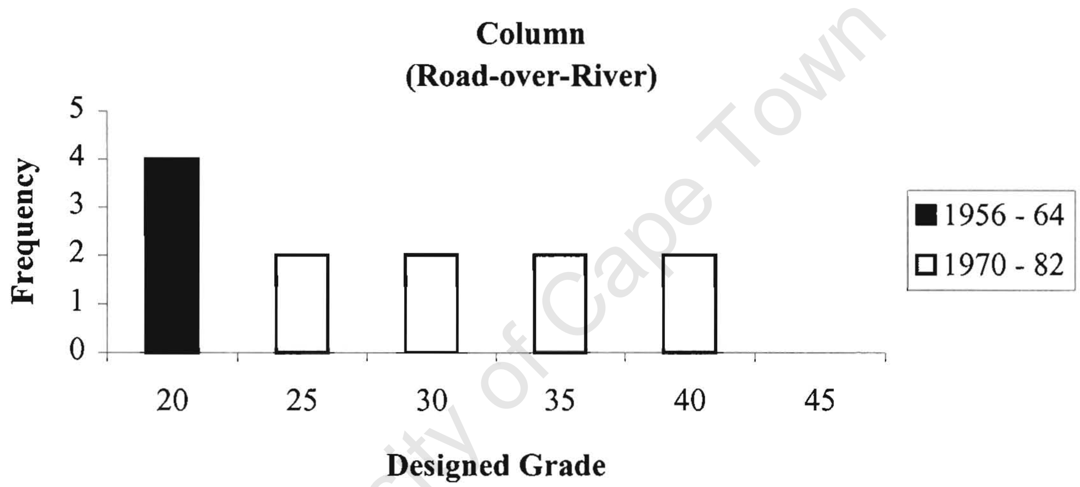

Column
(Road-over-Road)
Frequency
7
6
5
4
3
2
1
0
20
25
30
35
40
45
Design Grade
1970 - 82
1956 - 64

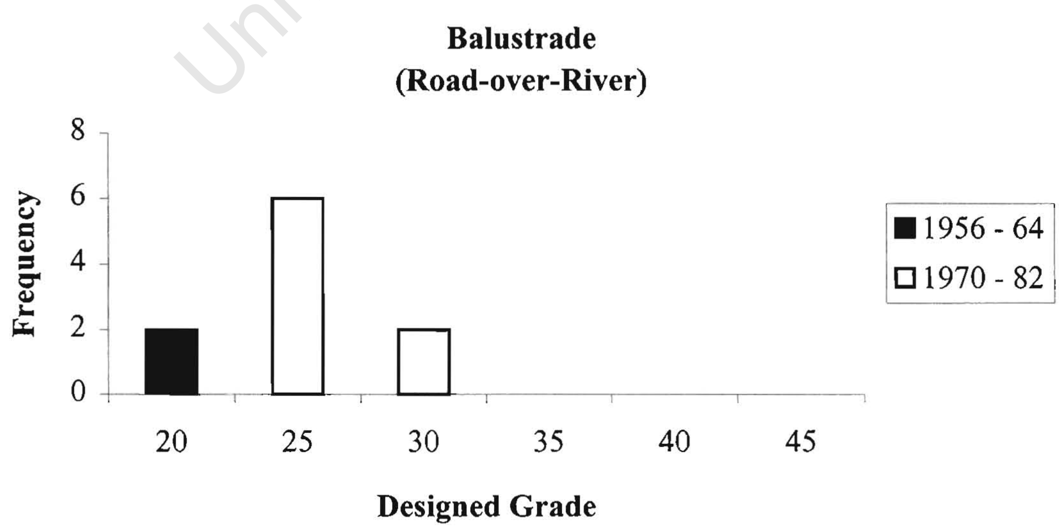

Balustrade
(Road-over-Road)
Frequency
12
10
8
6
4
2
0
20
25
30
35
40
45
Designed Grade
1970 - 82
1956 - 64


Wing Wall
(Road-over-Road)
Frequency
10
8
6
4
2
0
20
25
30
35
40
45
Designed Grade
1970 - 82
1956 - 64


Deck
(Road-over-River)
Frequency
5
4
3
2
1
0
20
25
30
35
40
45
Designed Grade
1970 - 82
1956 - 64


Abutment
(Road-over-River)
Frequency
6
4
2
0
20
25
30
35
40
45
Designed Grade
1956 - 64
1970 - 82


Column
(Road-over-River)
Frequency
5
4
3
2
1
0
20
25
30
35
40
45
Designed Grade
1956 - 64
1970 - 82


Balustrade
(Road-over-River)
Frequency
8
6
4
2
0
20
25
30
35
40
45
Designed Grade
1956 - 64
1970 - 82

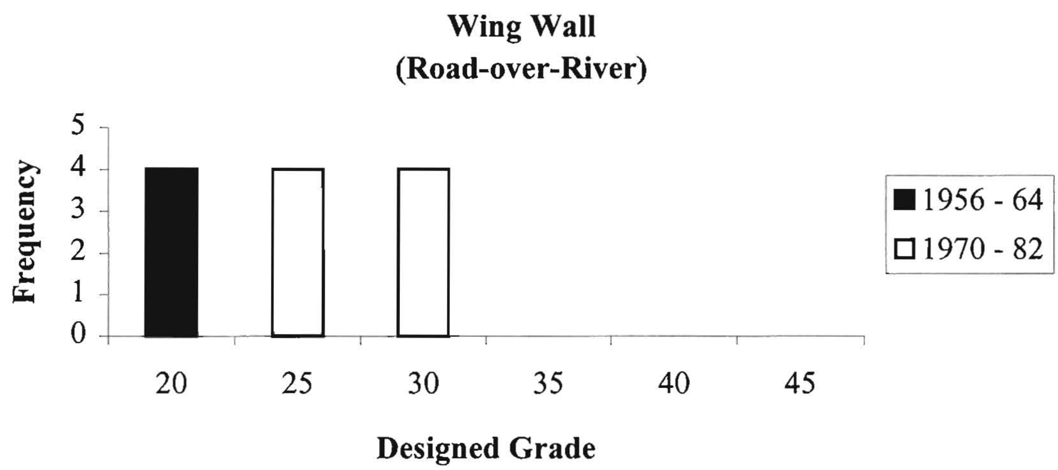


Figure 5.52: Data of the specified design concrete strength grade for different elements of road-over-road and road-over-river bridges in Durban-South Coast locality

Based on the analysis above, the design grade for the elements of the bridges in Johannesburg locality was assigned as follows. The bridges in the motorway system of the Greater Johannesburg were mainly constructed in the 1960s and early 1970s, taken to be typical of the 1956 – 1964 period, thus the design grade for all the bridge columns should be between Grade 20 and 25. However, Ballim and Lampacher (1996) stated that the concrete strength grade for these columns should be between a very wide range of Grade 20 to 40 based on historical records. Thus, the data in the motorway system in the Johannesburg city will be separated from the N3 data, and columns of the motorway system were assumed to be Grade 20-30. On the other hand, the bridges along the N3 freeway were mainly constructed in the late 1970s and thus they should belong to the 1970 – 1982 group. The concrete strength grade for each of these bridge elements (e.g. abutment of road-over-road bridges) of the N3 data are assumed to be the concrete strength grade with the highest frequency for the same bridge element of the same bridge type (i.e. abutment of road-over-road bridges) constructed in 1970 – 1982 in Durban locality. Generally speaking, all bridge elements except for the deck can be assumed to be Grade 25-30 elements whilst decks can be assumed to be Grade 35 which is the average of Grade 30 (for normal reinforced) and Grade 40 (for prestressed) (See Tables 4.8 and 4.9).

5.4.5 Derivation of Carbonation Prediction Models

For this locality, only the method of least squares will be employed due to the lack of early age data and the avoidance of the assignment of an "initial" point as explained for the Durban locality.

The data of the Greater Johannesburg Motorway System were analysed separately from those of the N3 freeway as explained earlier. The motorway system contains exposed and sheltered elements with an assumed grade of 20-30, whilst the N3 freeway includes exposed Grade 25-30 and sheltered Grade 30-35 elements.

The analytical procedures used in the present analysis will be the same as in the Durban locality. The important analytical results will be shown below followed by a detailed discussion, while the detailed procedures can be found in Appendix F.

(a) Johannesburg Motorway System

• Exposed Elements

Nominal Grade 20-30

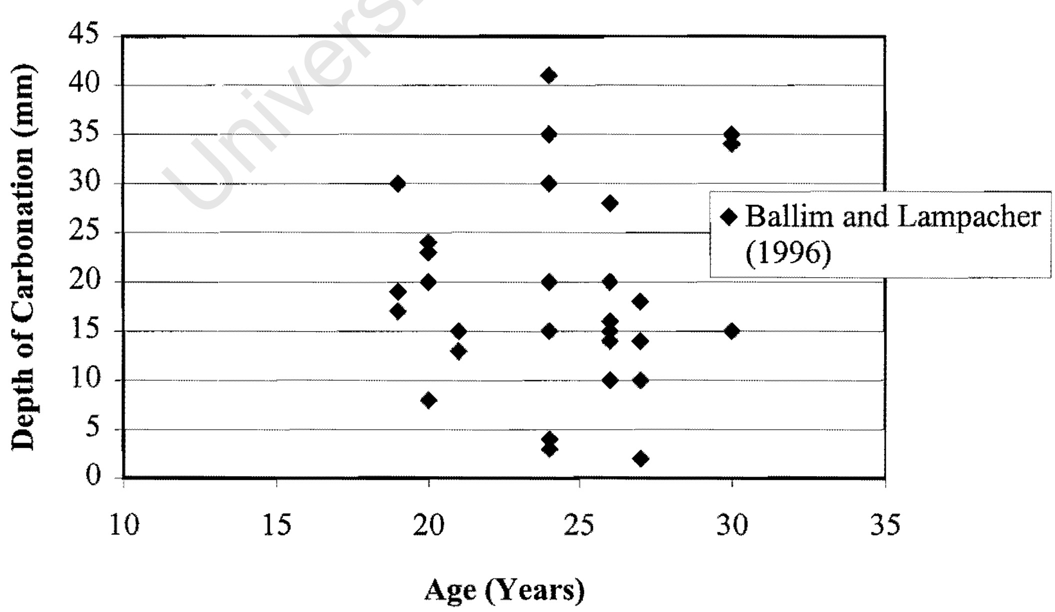


Figure 5.53: Carbonation results for exposed Grade 20-30 concrete columns of bridges of the motorway system in the Greater Johannesburg (all results)

Table 5.29: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 20-30 concretes for the Johannesburg motorway system

n	k	e^2
0.4	5.12	2326.0
0.5	3.72	2339.7

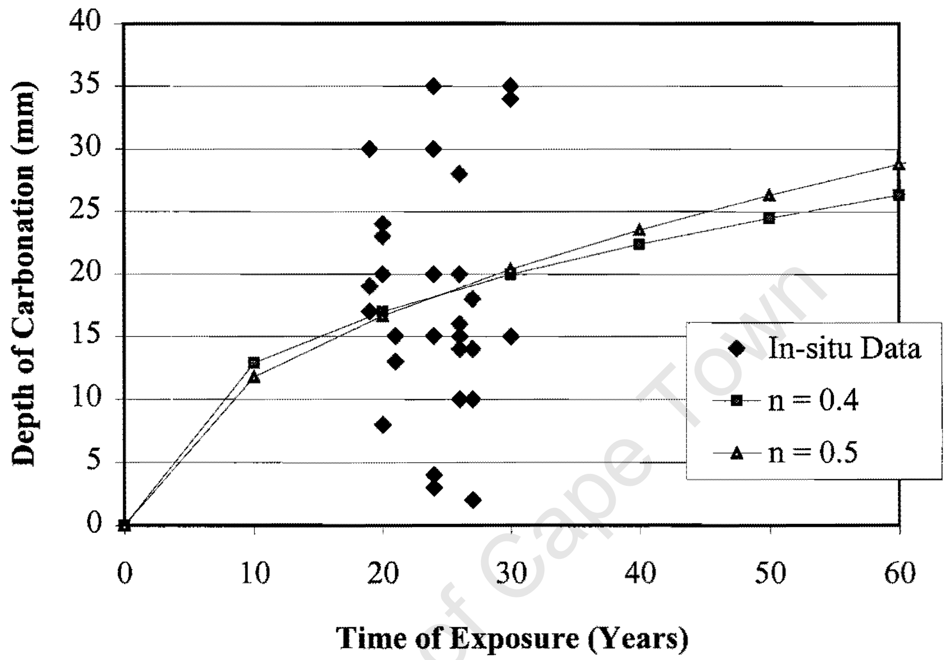


Figure 5.54: Carbonation predictions for different n values and field carbonation results (without gross outliers, 1 No.) for exposed Grade 20-30 concretes of bridges of the Johannesburg motorway system.

• Sheltered Elements

Nominal Grade 20-30

Table 5.30: Values of k and sum of squares of residuals (e^2) for fixed n-values for sheltered Grade 20-30 concretes for the Johannesburg motorway system

n	k	e^2
0.4	4.11	438.3
0.5	2.99	440.4

Note: The above results for n equals 0.4 contain an outlier, as for Grade 45 exposed concretes in Cape Peninsula locality, see section 5.2.6 (c).

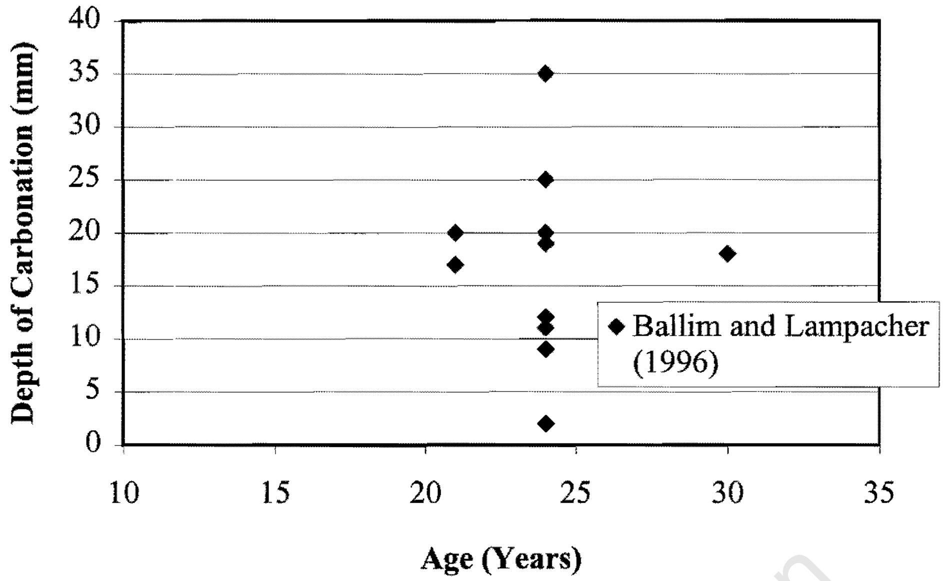


Figure 5.55: Carbonation results for sheltered Grade 20-30 concretes of Johannesburg motorway system (all results)

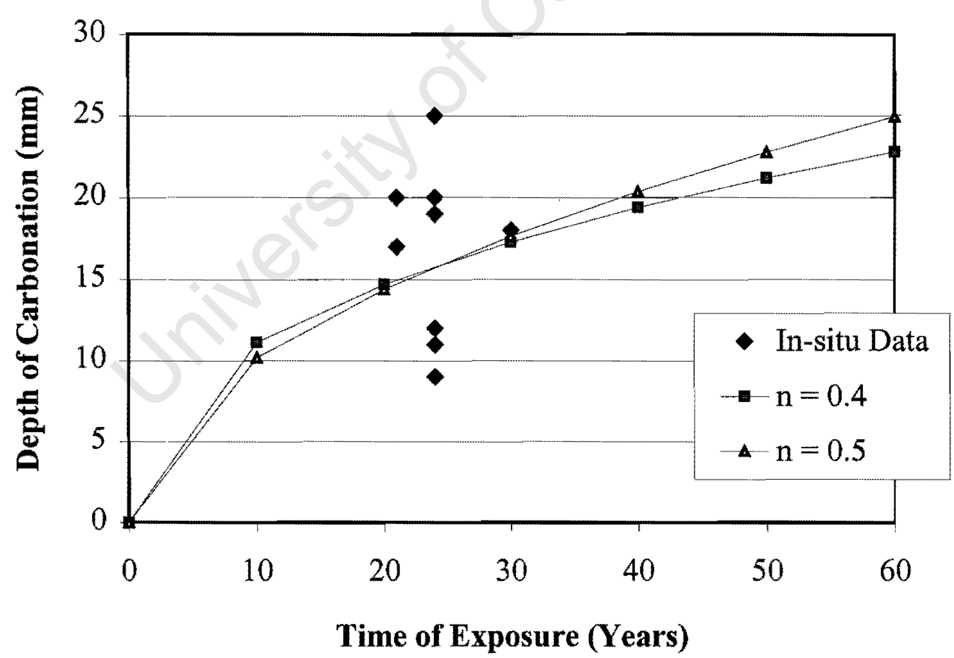


Figure 5.56: Carbonation predictions for different n values and field carbonation results (without gross outliers, 2 No.) for sheltered Grade 20-30 concretes of bridges of the Johannesburg motorway system.

• Comparison and Discussion

The selection of n value is based on the sum of squares of residuals (e^2) as well as the understanding of the process of carbonation. The e^2 given by the n values of 0.4 and 0.5 are very similar for both exposed and sheltered elements with a maximum difference of 0.6% (2326.0 and 2339.7, see Table 5.29) in exposed elements. This means the fitted models given by n equals 0.4 or 0.5 can fit the given data equally well (see Figure 5.54 and 5.56). However, the relative humidity for the Johannesburg locality throughout the year is within the optimum range of relative humidities for carbonation, thus a more conservative n value of 0.5 is more appropriate and therefore this n-value is chosen for this locality.

The comparison of the rate of carbonation for exposed and sheltered elements with n value of 0.5 is shown in Figure 5.57 below.

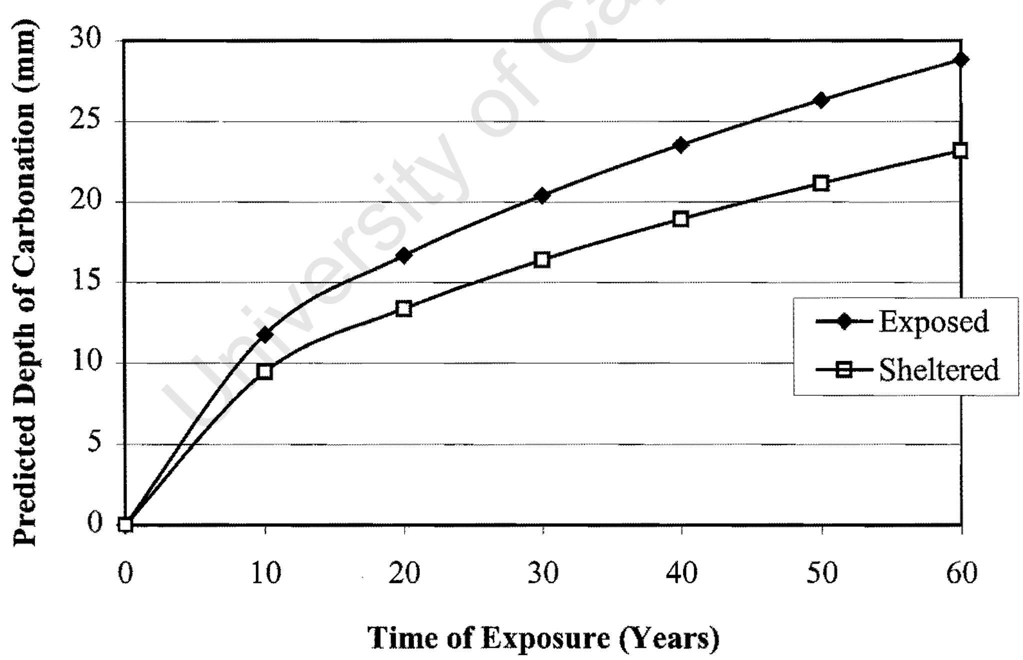


Figure 5.57: Carbonation prediction for exposed and sheltered Grade 20-30 concretes of the Johannesburg motorway system.

The carbonation rate of exposed elements is higher than that of sheltered elements in the motorway system of the Greater Johannesburg area. This statistical result is unexpected if the difference in the rates between these two types of elements is significant, as this contradicts the influence of near surface moisture content on the rate of carbonation. However, based on the understanding of the environmental conditions of this locality as well as their associated effects on the process of carbonation, the difference in carbonation for these two types of elements is small and may be ignored. In other words, the carbonation rate for both exposed and sheltered elements in this locality may reasonably be regarded as the same. This will be explained later in detail when discussing the analytical results of the bridges along the N3 freeway.

(a) N3 between Heidelberg Road and Geldenhuis Interchange

• Exposed Elements

Nominal Grade 25-30

Table 5.31: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 25-30 concretes along the N3 in Johannesburg locality

n	**k**	e^2
0.4	5.51	846.9
0.5	4.01	842.2

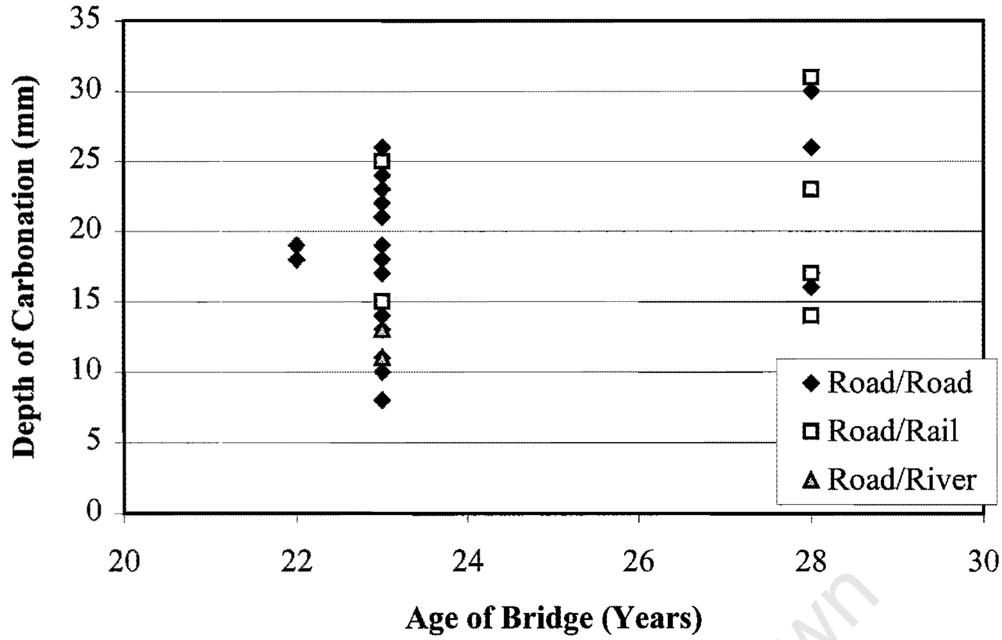


Figure 5.58: Carbonation results for exposed Grade 25-30 concretes along the N3 freeway in the Johannesburg locality (all results)

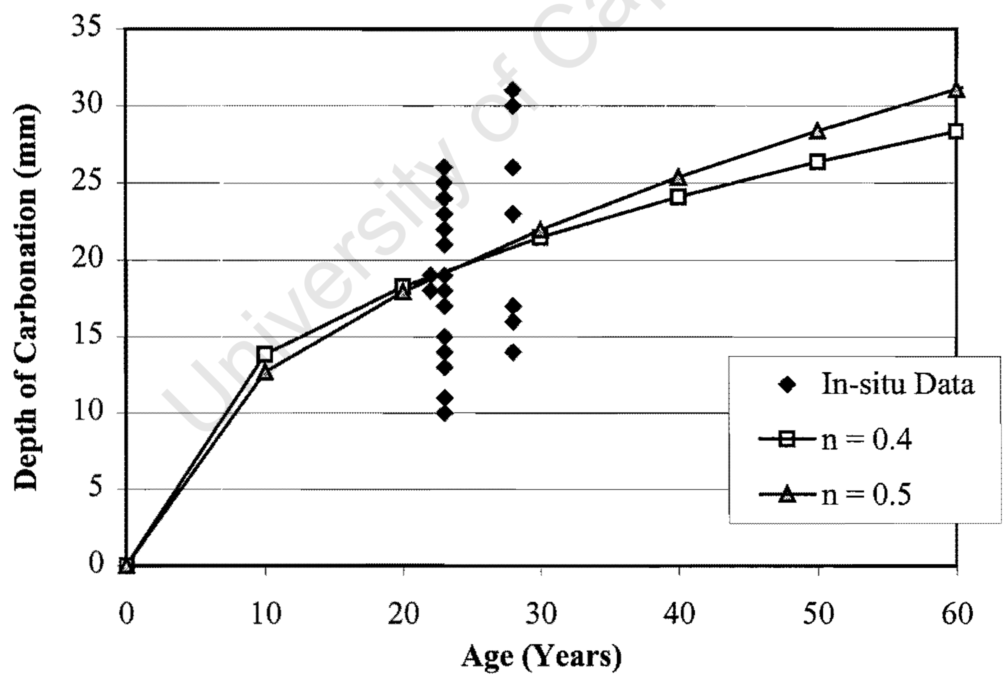


Figure 5.59: Carbonation predictions for different n values and field carbonation results (without gross outliers, 1 No.) for exposed Grade 25-30 concretes of bridges along the N3 in the Johannesburg locality

Nominal Grade 35

It should be noted that this nominal grade of concrete consists of carbonation results measured from sides of decks only. Based on the design concrete strength grades for the bridges in Durban locality, Grade 30 and Grade 40 was the common specified grade for normal reinforced and prestressed deck concrete respectively. Since this information for the bridges is not available, the deck is analysed separately from other bridge elements and taken to be Grade 35 concretes, being the average grades for reinforced and prestressed concretes.

Table 5.32: Values of k and sum of squares of residuals (e^2) for fixed n-values for exposed Grade 35 concretes along the N3 in Johannesburg locality

n	k	e^2
0.4	4.42	279.5
0.5	3.20	286.8

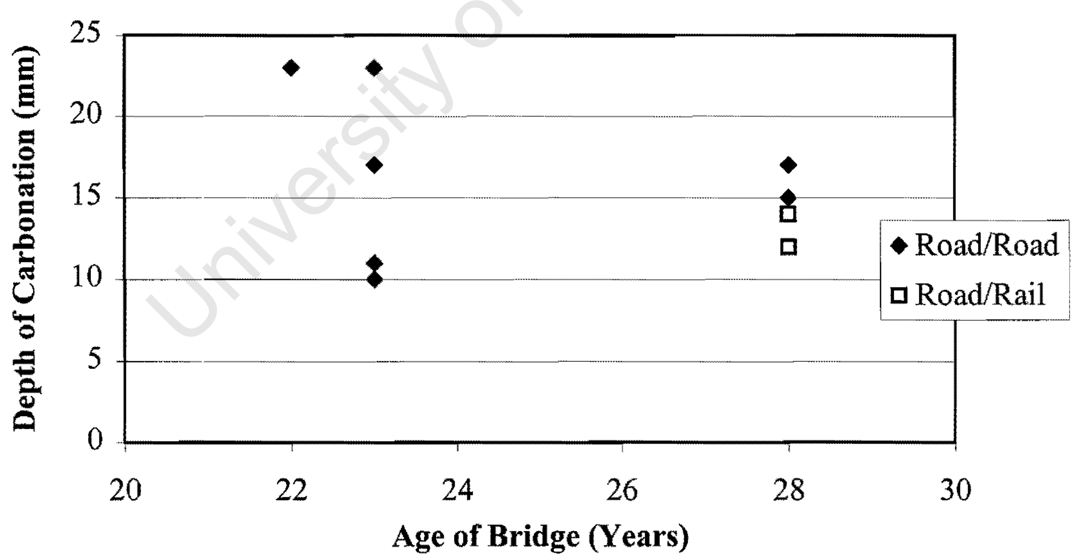


Figure 5.60: Carbonation results for exposed Grade 35 concretes along the N3 freeway in the Johannesburg locality (all results)

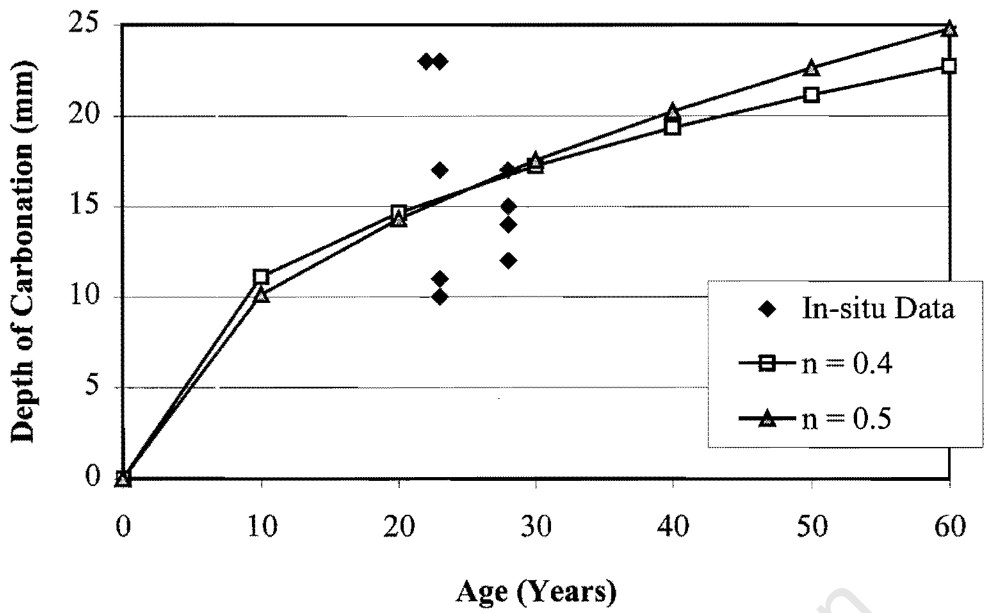


Figure 5.61: Carbonation predictions for different n values and field carbonation results (no gross outliers were detected) for exposed Grade 35 concretes of bridges along the N3 in the Johannesburg locality

• Sheltered Elements

Nominal Grade 30-35

This nominal grade consists of abutments and deck soffits. Based on the strength grade data given in Figure 5.52, the abutments could be assumed to be Grade 30 (the grade with the highest frequency). The deck soffits can be taken as Grade 35 as explained above.

Table 5.33: Values of k and sum of squares of residuals (e^2) for fixed n-values for sheltered Grade 30-35 concretes along the N3 in Johannesburg locality

n	**k**	**e^2**
0.4	5.42	498.9
0.5	3.95	498.7

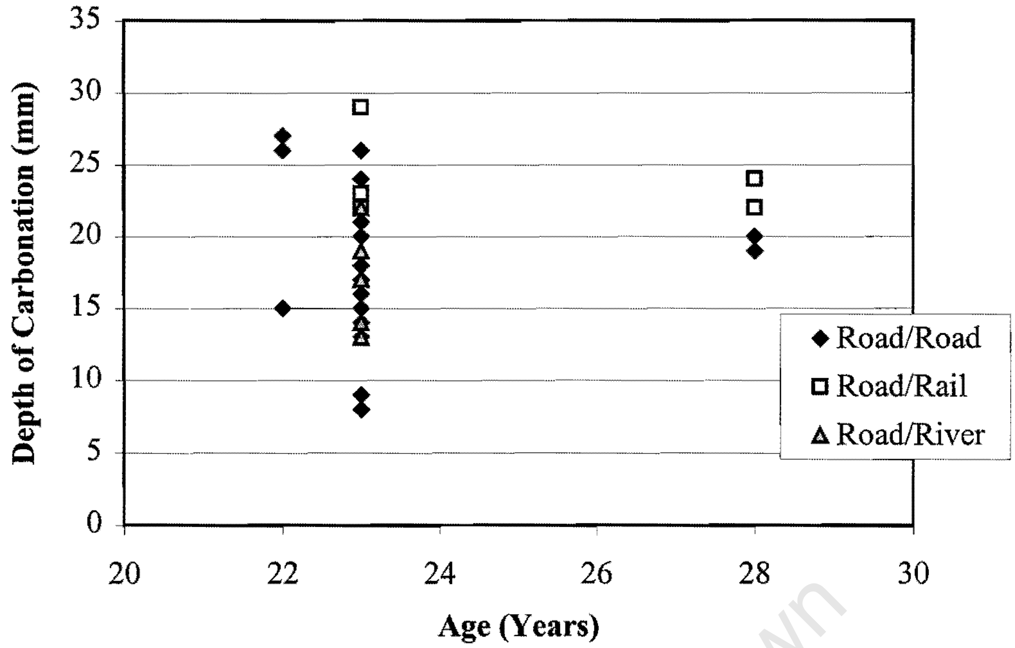


Figure 5.62: Carbonation results for sheltered Grade 30-35 concretes along the N3 freeway in the Johannesburg locality (all results)

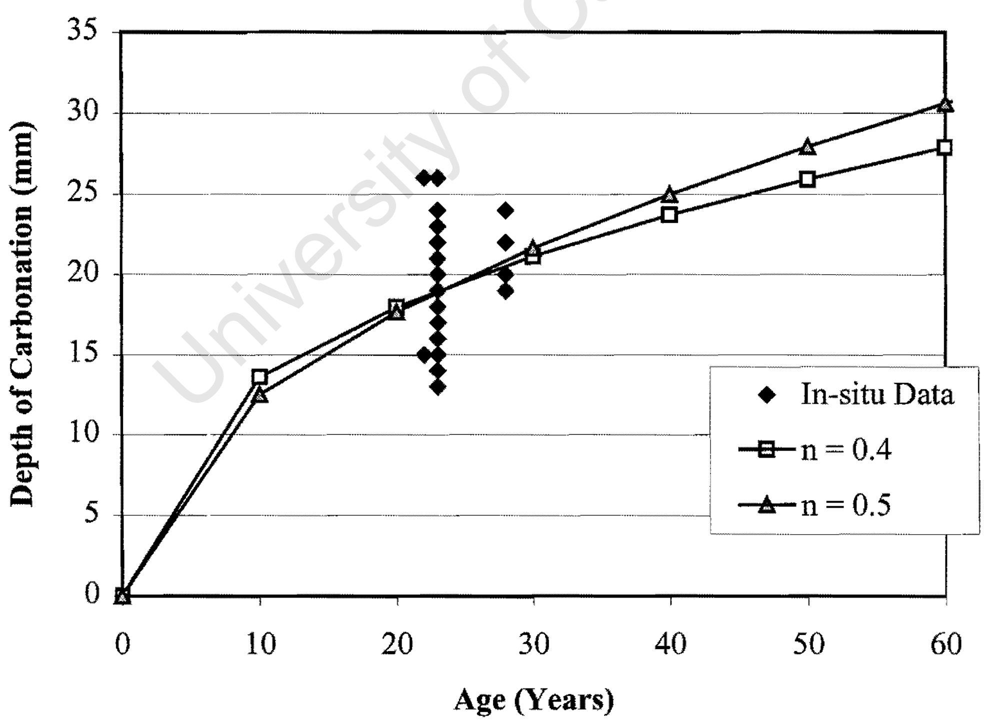


Figure 5.63: Carbonation predictions for different n values and field carbonation results (without gross outliers, 4 No.) for exposed Grade 30 - 35 concretes of bridges along the N3 in the Johannesburg locality.

• Comparison and Discussion

The n value for this data set for both exposed and sheltered elements is chosen to be 0.5 as explained above, since the present locality has a relative humidity which favours carbonation of concrete.

The carbonation rates for the exposed and sheltered elements from the bridges along the N3 freeway, based on the selected n value of 0.5, are shown graphically in Figure 5.64.

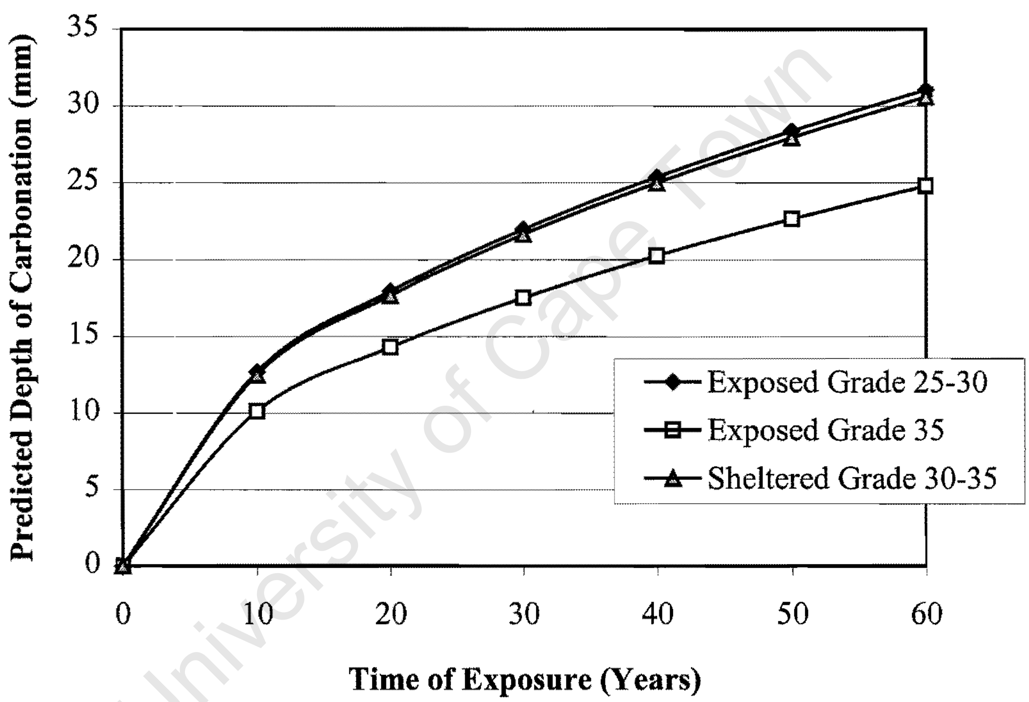


Figure 5.64: Carbonation predictions based on the bridges along the N3 freeway in the Johannesburg locality

The carbonation rate of exposed Grade 25 – 30 is higher than that of exposed Grade 35 which is attributed to its higher permeability. The carbonation rate of sheltered Grade 30 – 35 is practically the same as that of exposed Grade 25 – 30, whilst it is higher than that of exposed Grade 35. The minimal difference may be mainly due to the environmental (climatic) conditions in this locality, rather than the material effects. The environmental conditions broadly include the rainfall patterns that occur in the high rainfall season as well as the relative humidity throughout the year. Rainfall in the Johannesburg locality is in the form of showers and thunderstorms and generally of a short duration (see section 4.3.3). In addition, the relative humidites for both high and low rainfall seasons are low (see Table 4.4). The short duration of rainfall and low relative humidity make the near surface moisture content of the exposed elements to be essentially no different in comparison with the sheltered elements. This is because the short duration of rainfall can only induce a relatively shallow "wetted depth" at the surfaces of the exposed elements. The concrete pores within this shallow "wetted depth" will dry quickly and revert to the external relative humidity (after being wetted by rain) in a short period of time as the "wetted depth" is shallow and the concretes are allowed to dry in an environment of low relative humidity. Thus, it is reasonable that exposed and sheltered elements have similar carbonation rates in this locality.

Also according to Figure 5.64, it can be seen that the carbonation rate of sheltered Grade 30 – 35 is more comparable to exposed Grade 25 – 30. This may indicate that the concrete strength grade of the sheltered Grade 30 – 35 elements were dominantly Grade 30. Nevertheless, it may be reasonable to combine these two carbonation results as one group in the calculation of percentile carbonation depths owing to the climatic conditions of this locality, and the fact that they do not differ substantially, as well as the true grade information for these elements not being known.

Generally speaking, the carbonation results from the Greater Johannesburg Motorway System can be combined with the carbonation results of the N3 freeway as illustrated in Figure 5.65 and all the prediction models are summarised in Table 5.34.

Table 5.34: Summary of all carbonation prediction models for the Johannesburg locality (including Ballim and Lampacher's (1996) prediction model)

Data Set	Concrete Strength Grade Group	Prediction Model
1. Motorway System	Exposed Grade 20 – 30*	$d_c = 3.72t^{0.5}$
	Sheltered Grade 20 - 30	$d_c = 2.99t^{0.5}$
2. Along the N3 between Heidelberg and Geldenhuis Interchange	Exposed Grade 25 – 30$^{\Psi}$	$d_c = 4.01t^{0.5}$
	Exposed Grade 35	$d_c = 3.20t^{0.5}$
	Sheltered Grade 30 - 35	$d_c = 3.95t^{0.5}$
3. Ballim and Lampacher (1996)	Both Exposed and Sheltered Grade 20 – 30 of Motorway System	$d_c = 3.76t^{0.5}$

Note: * and $^{\Psi}$ can be combined to form one prediction model for exposed Grade 20-30 elements as $d_c = 3.76t^{0.5}$ based on method of least squares with n = 0.5, see below and Appendix F.

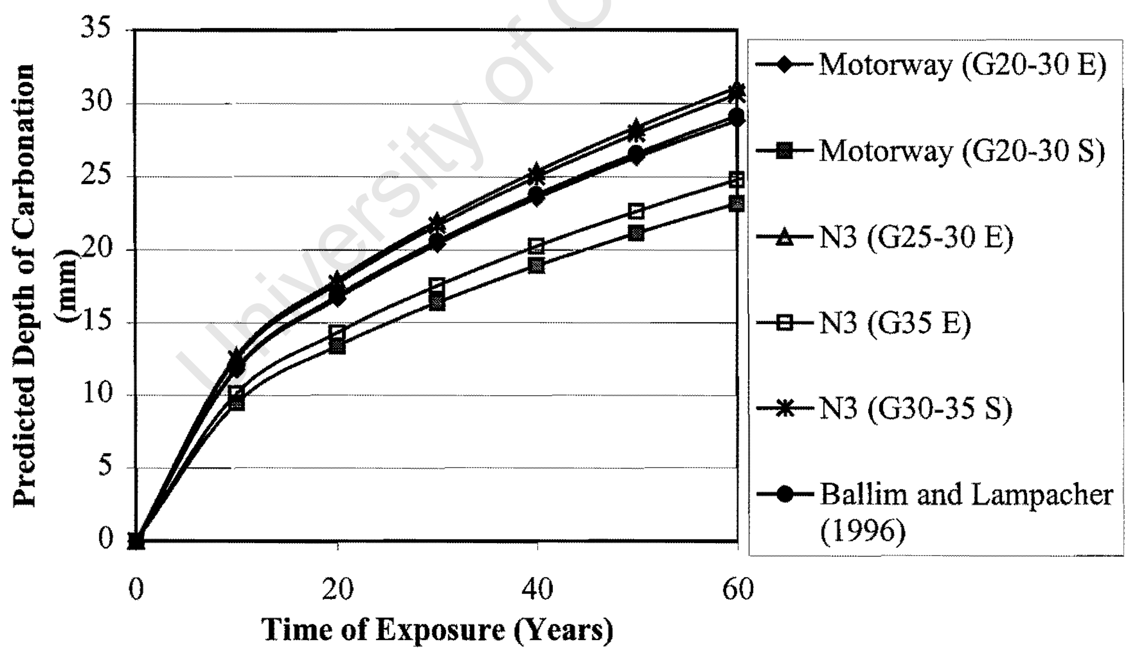


Figure 5.65: Carbonation predictions for all exposed and sheltered elements in the Johannesburg locality ("G", "E" and "S" represent Grade, exposed and sheltered elements respectively. "Ballim and Lampacher (1996)" refers to their prediction model based on both exposed and sheltered elements in the Motorway System).

Carbonation results from the Grade 20 – 30 exposed elements of Motorway System, Grade 25 – 30 exposed elements and Grade 30 – 35 (presumably with Grade 30 elements dominant) sheltered elements of the N3, as well as the prediction model derived by Ballim and Lampacher (1996) show very similar carbonation rates. This supports the above arguments of rainfall pattern and the low relative humidity of this locality that make the carbonation rates for both exposed and sheltered elements similar as long as they have a similar concrete quality (in terms of concrete strength grade in this thesis). Also, it is advisable to combine "Motorway (G20-30 E)" with "N3 (G25-30 E)" as one prediction model for Grade 20-30 exposed elements only.

Grade 35 exposed elements from the N3 freeway and Grade 20 – 30 sheltered elements from the Greater Johannesburg Motorway System exhibit a relatively low rate of carbonation. Better concrete quality (higher strength grade) for the former accounts for a lower carbonation rate than the other lower strength grade concretes. The latter having a low rate of carbonation may be due to the lesser number of carbonation results (11 results), compared with Grade 20 – 30 exposed elements from the Greater Johannesburg Motorway System (31 results). Nevertheless, based on the climatic conditions of this locality, carbonation rates for exposed and sheltered elements with similar concrete strength grade are similar. It may therefore be reasonable to view the exposed and sheltered elements for the Greater Johannesburg Motorway System as one group.

From above, the carbonation prediction models for both motorway system of the Greater Johannesburg and the bridges along the N3 are very similar for the similar concrete strength grade. This suggests that it is sensible to combine these data when calculating the percentile carbonation depth given in section 5.6.

5.5 COMPARISON OF CARBONATION RATES BETWEEN THE THREE LOCALITIES

Chapter 3 mentioned that the rate of carbonation is affected by 2 main factors, namely, materials and environmental. Therefore, the rate of carbonation for different regions with different materials and environmental conditions is different and hence, when deriving a carbonation prediction model for a particular region, in-situ data from that region should be used. In this thesis, carbonation of concrete in three South African localities, namely, the Cape Peninsula, Durban and Johannesburg localities, is being studied by means of gathering in-situ data and analysing them for each of these localities separately. The rate of carbonation based on statistical analysis and scientific principles were discussed in previous sections. It can be seen that the carbonation rates for these three localities are different. This can be explained, as far as this thesis is concerned, mainly by the climatic conditions of these localities. Materials effects on the rate of carbonation in these three localities are difficult to quantify as there was no information on the exact materials that were used for the construction of the bridges under investigation, besides the binder type (which was, in general, assumed). Therefore, this factor will be ignored. However, when comparing the carbonation predictions for each locality, only the same grade of concrete (same concrete quality) from each locality will be used in order to allow for the material effects as far as possible.

Chapter 4 reported the climatic conditions for each locality. The three localities have different climatic conditions in terms of relative humidity and temperature, which have a great impact on the rate of carbonation. Because of these climatic differences, the rate of carbonation of each of these localities is not the same. In this section, the different rates of carbonation for these localities will be compared and discussed.

5.5.1 Concrete Strength Grade

The design concrete strength grades that were analysed for all localities were given in Table 5.35. It should be noted that the prediction models for the exposed and sheltered elements in Durban and Johannesburg localities will be combined only in the evaluation of the percentile carbonation depths. This is because for the comparison of the carbonation rates between these localities, it is better to keep the exposure conditions the same (see the next section).

Table 5.35: Carbonation prediction models for all localities

Locality	Design Strength Grade	Prediction Model
Cape Peninsula	Exposed Grade 20	$d_c = 3.47t^{0.4}$
	Exposed Grade 30	$d_c = 2.58t^{0.4}$
	Exposed Grade 40	$d_c = 2.04t^{0.4}$
Durban (1970 – 1982)	Exposed Grade 20 - 25	$d_c = 4.93t^{0.4}$
	Exposed Grade 30 - 35	$d_c = 3.75t^{0.4}$
	Sheltered Grade 20 - 25	$d_c = 4.82t^{0.4}$
	Sheltered Grade 30 - 35	$d_c = 3.44t^{0.4}$
	Sheltered Grade 40 - 45	$d_c = 2.64t^{0.4}$
Johannesburg	Exposed Grade 20 – 30	$d_c = 3.76t^{0.5}$
	Exposed Grade 35	$d_c = 3.20t^{0.5}$
	Sheltered Grade 20 – 30	$d_c = 2.99t^{0.5}$
	Sheltered Grade 30 - 35	$d_c = 3.95t^{0.5}$

5.5.2 Exposure Conditions

It is meaningful to make comparisons of the prediction models for the localities which have similar concrete strength grade, as well as similar exposure conditions. Although as shown in previous sections that for Durban and Johannesburg localities, there were no substantial differences in carbonation rates for the exposed and sheltered elements with the same concrete grade, it is more sensible to compare the carbonation predictions for the localities with similar concrete quality and exposures in order to have a better understanding of the climatic effects on the carbonation rates. Therefore, according to Table 5.35, two concrete grades, namely, Grade 20 – 30 and Grade 30 -- 35, can be used to compare the climatic effects on the rate of carbonation in the three localities.

5.5.3 Climatic Effects on Rate of Carbonation

Figure 5.66 and Figure 5.67 show the comparison of carbonation prediction for the similar design concrete strength grades (between Grade 20 and 30 as well as Grade 30 - 35) and exposures (all exposed to sun, rain and wind) for the Cape Peninsula, Durban and Johannesburg localities.

For these two concrete strength grades, Johannesburg locality has the highest rate of carbonation, whilst Durban locality has a higher rate of carbonation than the Cape Peninsula locality. It is to be expected that the Johannesburg locality has the highest rate of carbonation as its relative humidities for both high and low rainfall seasons of 68% and 51% respectively (see Table 4.4), are within the optimum range for carbonation.

Although the relative humidities for both high and low rainfall seasons in Durban and the Cape Peninsula localities are very similar (see Table 4.4), with significant carbonation proceeding mainly in the low rainfall season, Durban locality has a higher rate of carbonation than the Cape Peninsula locality. Thus, besides the effects of relative humidity on the rate of carbonation, this suggests that temperature and rainfall pattern also play an important role in carbonation rate, especially if two regions or localities have similar relative humidity. In the low rainfall season, the relative humdities and the temperature for these two localities are very similar. However, in the high rainfall season, the temperature for Durban locality is 9°C higher than the Cape Peninsula locality. The higher the temperature, the faster the rate of carbonation.

In addition, the rainfall pattern can also be expected to have an effect on the carbonation rate. In Durban and Johannesburg localities, short duration rainfall allows the near-surface moisture content of the exposed elements to revert to the ambient relative humidity after being wet in a relatively short period of time. Therefore, the effects of rain on the rate of carbonation for the exposed elements in these two localities are not substantial. On the other hand, a relatively long duration of rainfall and wet weather in the Cape Peninsula locality has a more significant effect on hindering the process of carbonation (and hence lowering the carbonation rate) as the near-surface pores of the exposed elements stay wet for a longer period of time.

For the above reasons, Johannesburg locality should have the highest rate of carbonation, whilst the Cape Peninsula locality should have the lowest rate of carbonation.

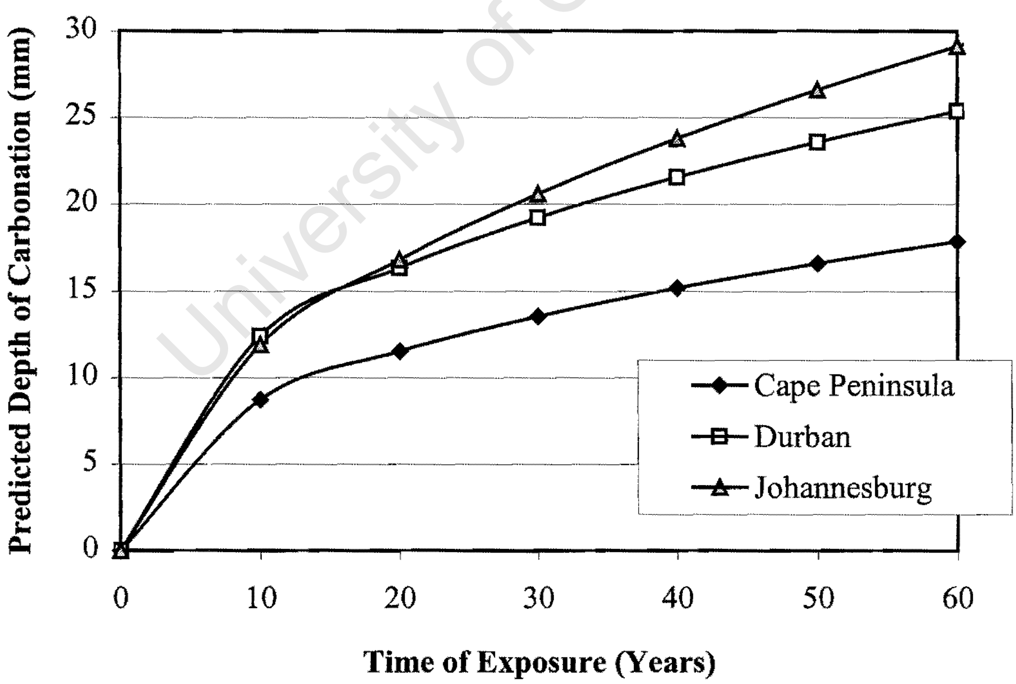


Figure 5.66: Comparison of carbonation rates of exposed Grade 20 – 30 concretes for the Cape Peninsula, Durban and Johannesburg localities

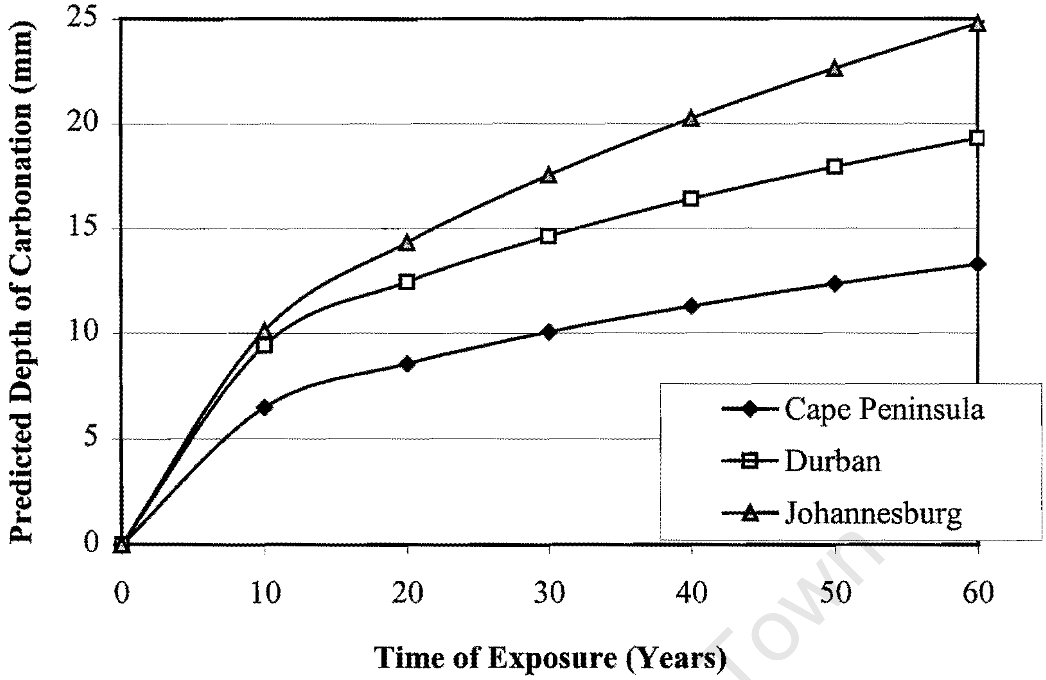


Figure 5.67: Comparison of carbonation rates of exposed Grade 30 – 35 concretes for the Cape Peninsula, Durban and Johannesburg localities

5.6 Carbonation Prediction Models for Different Percentile Values

It is more useful to predict the carbonation depth for the concrete strength grade bands which were investigated in the previous sections in a probabilistic way in order to have a more realistic prediction model with a higher "factor of safety" to allow for the highly variable conditions for the field concretes. This can be achieved by computing appropriate percentile carbonation depth values based on carbonation field data (after the elimination of all gross outliers). By way of illustration, a detailed procedure for the computation of percentile carbonation depth values for Grade 20 exposed concretes in the Cape Peninsula locality is shown below. The results for other concrete strength grade bands for the three localities will be given in this section and the detailed computational procedures can be found in Appendix G.

5.6.1 Cape Peninsula Locality

The percentile carbonation depth value depends on the percentile carbonation coefficient (i.e. k in equation 5.1), because the power series constant, n (in equation 5.1), is chosen and fixed to be 0.4 for this locality (according to the analysis in section 5.2.6 (c)). In other words, looking at the cumulative distribution function of the k values, the percentile carbonation depth values can be evaluated. Table 5.36 explains the procedures for computing the percentile k values.

Table 5.36: Percentile carbonation coefficient (k) for exposed Grade 20 concretes in the Cape Peninsula locality

Age (t)	Strength	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.4}$)	(mm/year$^{0.4}$)		(P<d)	
33	27.7*	17	4.20	1.53	1	0.06	0.10
33	27.7	10	2.47	1.75	2	0.12	0.12
40	30*	23	5.26	1.93	3	0.18	0.15
42	23.1	27	6.05	2.12	4	0.24	0.18
42	30	26	5.83	2.14	5	0.29	0.18
45	26.1	25	5.45	2.31	6	0.35	0.21
45	30*	8	1.75	2.47	7	0.41	0.24
45	30*	7	1.53	3.53	8	0.47	0.49
47	22.5	9	1.93	3.86	9	0.53	0.57
47	30*	18	3.86	4.09	10	0.59	0.63
47	30*	10	2.14	4.20	11	0.65	0.66
47	30*	21	4.50	4.50	12	0.71	0.73
67	30*	19	3.53	5.26	13	0.76	0.86
67	30*	22	4.09	5.45	14	0.82	0.89
75	30*	13	2.31	5.83	15	0.88	0.93
76	30*	12	2.12	6.05	16	0.94	0.94
			Average	**3.56**			
			Std. Dev.	**1.56**			

The carbonation coefficient (k) for each data point was calculated by dividing the measured carbonation depth (d_c) by "Age$^{0.4}$". The k values were then sorted in ascending order (in terms of magnitude) and ranked. The cumulative frequency (reported as "Probability") for each "sorted k" was calculated using equation 5.3 (Chatfield (1970)), and plotted in Figure 5.68. The "NormDist" function (see section 5.2.6 (a) for more detail) is also plotted in Figure 5.68.

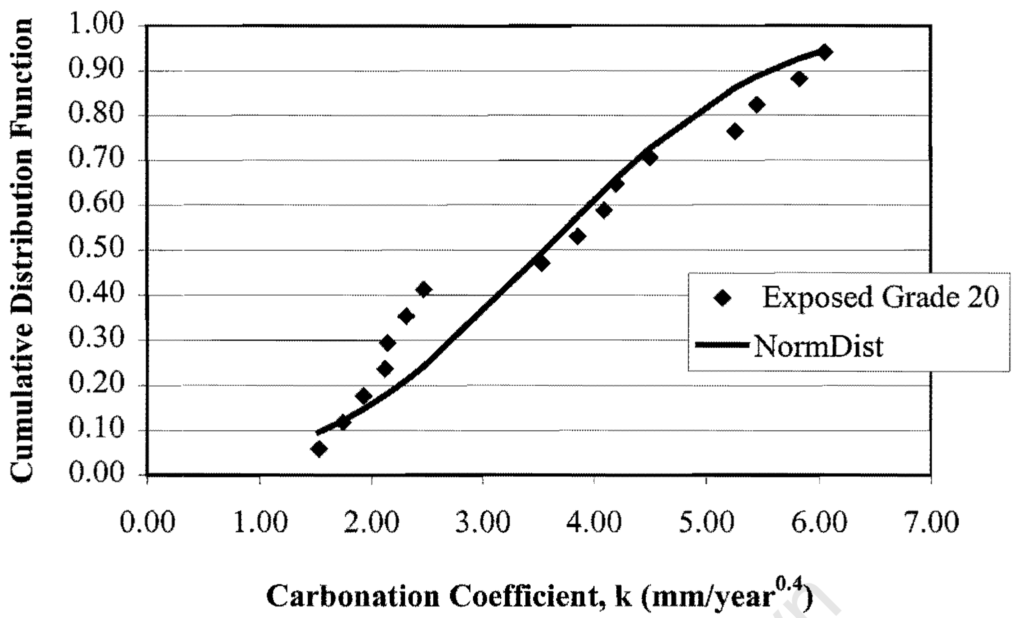


Figure 5.68: Percentile carbonation coefficient (k) values for exposed Grade 20 concretes in the Cape Peninsula locality

The k values obtained from the in-situ data are approximately normally distributed. The "NormDist" curve can be viewed as a "best-fit" curve to the k values. Therefore, the percentile k values can be obtained from the "NormDist" curve. For example, the 90th percentile k value equals the k value on the "NormDist" curve with a cumulative distribution value of 0.9 in Figure 5.68. In simple statistical terms, this percentile k value represents 90% of the in-situ data having less than or equal to this k value. With different percentile k values, the corresponding percentile carbonation depths can be calculated by using equation 5.1.

Several percentile carbonation coefficient (k) values were selected and the corresponding percentile carbonation depths for concrete in the Cape Peninsula locality are shown in Figure 5.69 – 5.71.

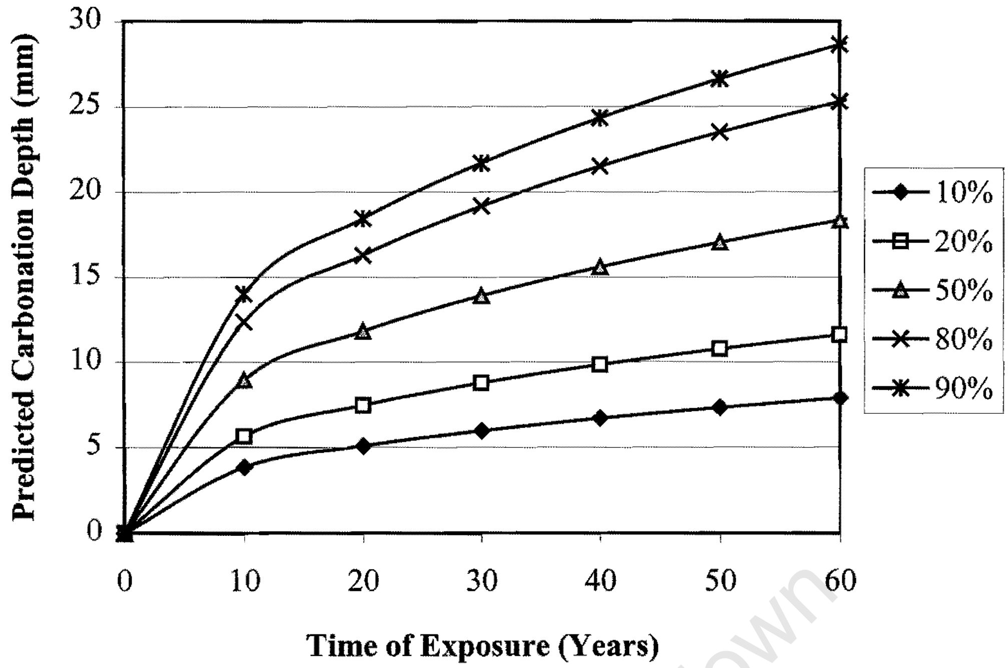


Figure 5.69: Selected percentile carbonation depths for exposed Grade 20 concretes in the Cape Peninsula locality

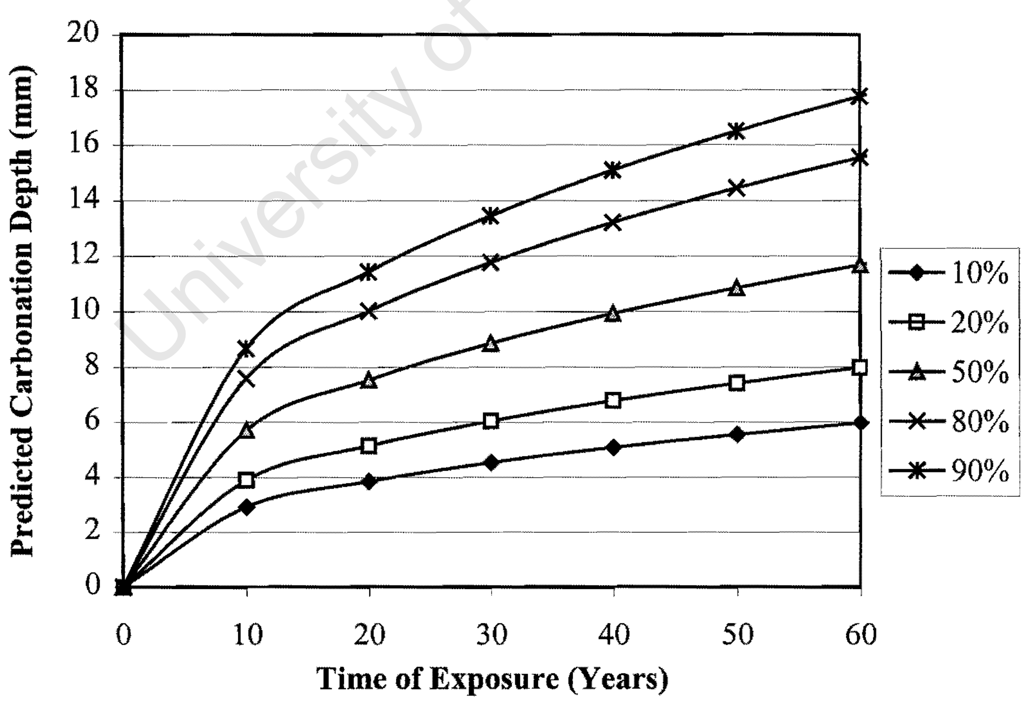


Figure 5.70: Selected percentile carbonation depths for exposed Grade 30 concretes in the Cape Peninsula locality

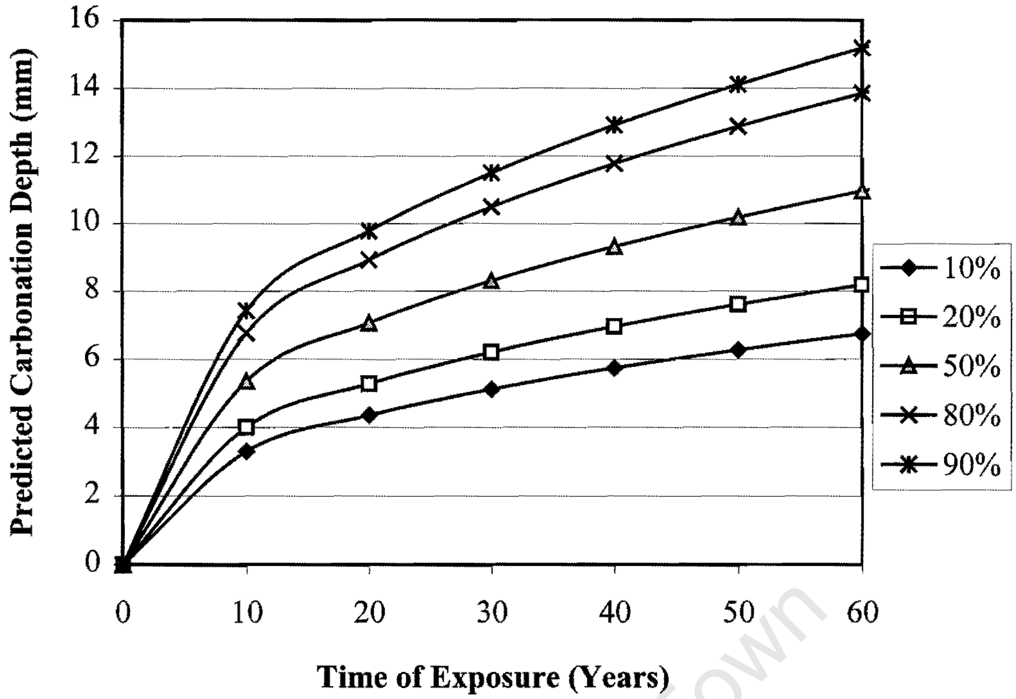


Figure 5.71: Selected percentile carbonation depths for exposed Grade 40 concretes in the Cape Peninsula locality

By way of example, assuming after 50 years that no more than 20% of steel should be in the carbonated zone for Grade 20 concretes, this implies that the minimum cover should therefore be 24 mm, while for Grades 30 and 40 concretes, the minimum cover is required to be only about 14 mm. Therefore, cover is less critical for higher grade concretes in terms of carbonation. Furthermore, the Code (SABS 0100 (1992)) requires a minimum cover depth of 40 mm, which is more than adequate under these conditions.

It would be useful to choose the confidence limits for the carbonation depth for all three concrete grades based on the findings from the above percentile carbonation depth values. These confidence limits represent the upper and lower carbonation depths with time of exposure. The candidate upper carbonation depths are 90th and 80th percentile carbonation depth values, and the lower are 10th and 20th percentile values from the previous section. The percentile carbonation depth values of 90% and 10% represents 80% confidence limits whilst 80% and 20% represents 60% confidence limits. Figure 5.72 shows the 80% confidence limits for the three grades of concrete in the present locality. 80% confidence limits is chosen rather than 60% due to a higher statistical reliability.

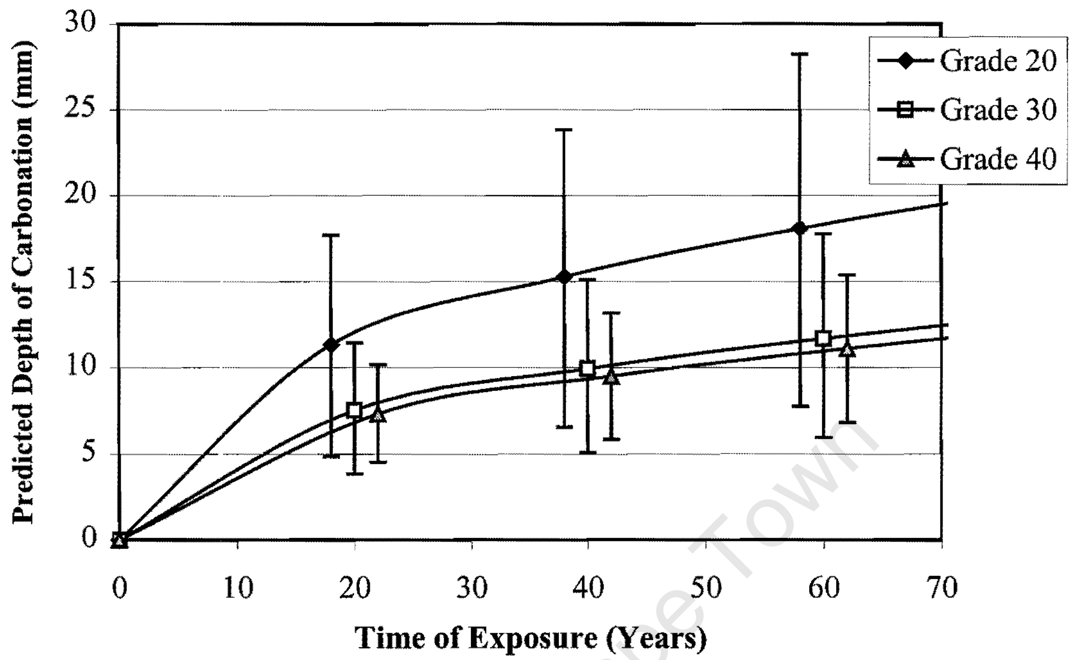


Figure 5.72: 80% Confidence limits for concretes in the Cape Peninsula locality

It can be seen that the confidence limits of Grade 40 concretes are overlapping with the confidence limits of Grade 30 concretes. This indicates that the maximum and minimum predicted depths of carbonation for these two concrete grades are very similar, as explained previously. On the other hand, the upper limit of Grade 20 concretes differs markedly from the other two concrete grades, indicating that the carbonation rate of Grade 20 concretes is substantially faster than the other concrete grades.

5.6.2 Durban Locality

It has shown that the carbonation rate for exposed and sheltered elements is very similar and therefore the data of these two types of elements can be combined together. Four groups were formed, namely, Grade 20 – 25 (1956 – 1964), Grade 20 – 25 (1970 – 1982), Grade 30 – 35 (1970 – 1982) and Grade 40 – 45 (1970 – 1982).

The percentile carbonation depths for each of these groups are shown in Figure 5.73 – 5.76.

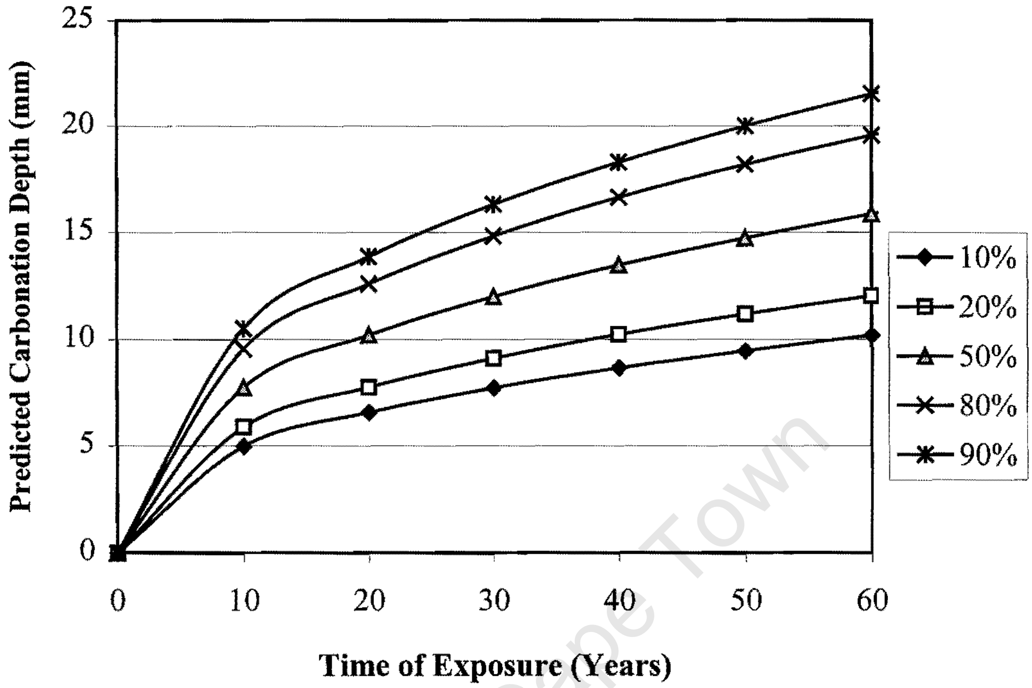


Figure 5.73: Selected percentile carbonation depths for exposed Grade 20 – 25 (1956 – 1964) concretes in Durban locality

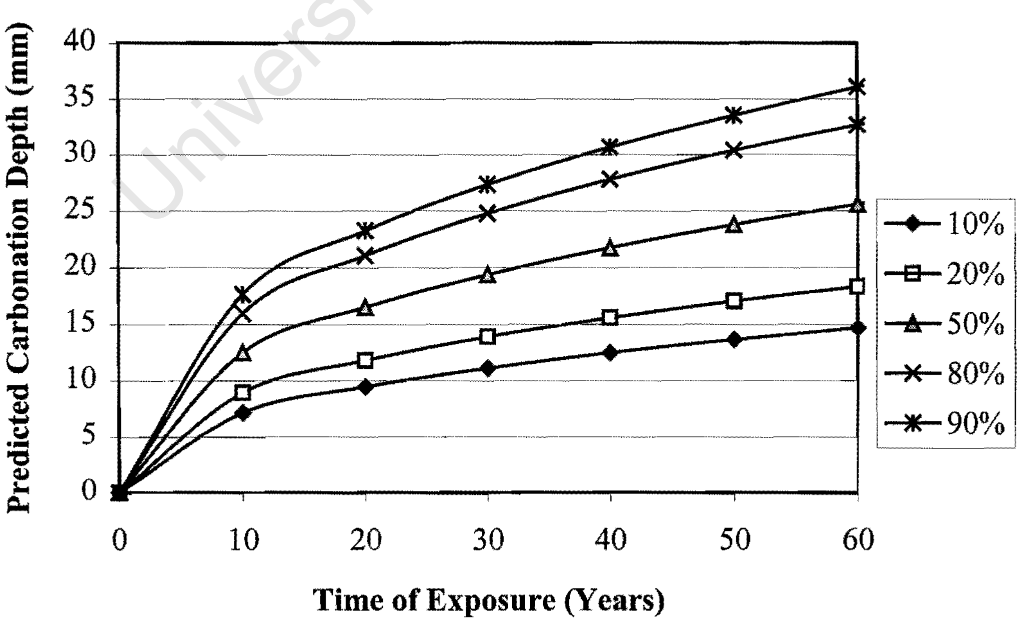


Figure 5.74: Selected percentile carbonation depths for exposed Grade 20 – 25 (1970 – 1982) concretes in Durban locality

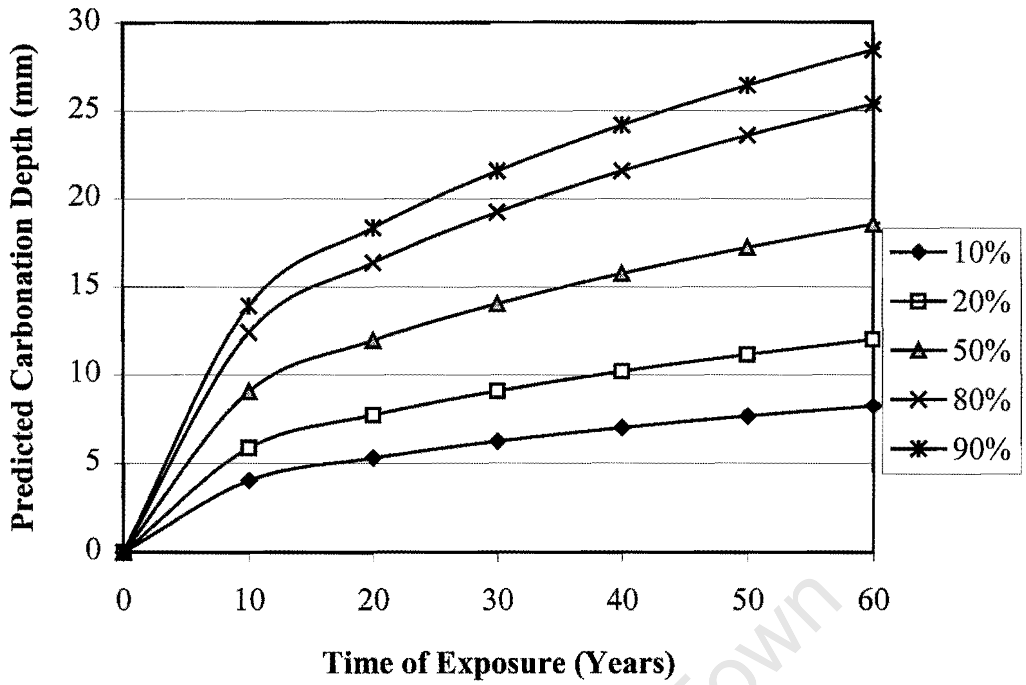


Figure 5.75: Selected percentile carbonation depths for exposed Grade 30 – 35 (1970 – 1982) concretes in Durban locality

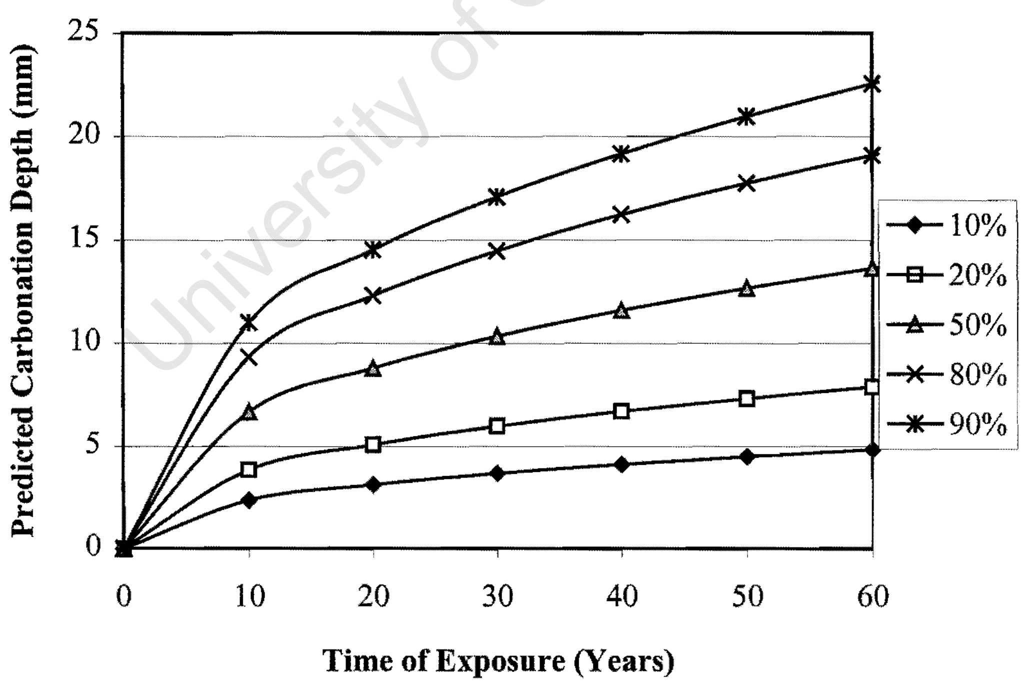


Figure 5.76: Selected percentile carbonation depths for exposed Grade 40 – 45 (1970 – 1982) concretes in Durban locality

A minimum cover of 18 mm is sufficient for Grade 20 – 25 concretes constructed between 1956 and 1964 with 20% steel in the carbonated zone for 50 years of exposure. In contrast, a minimum of 30 mm for the same grade band of concretes under the same conditions but constructed in 1970 – 1982. For Grades 30 - 35 (1970 – 1982) and 40 – 45 (1970 – 1982), a minimum cover of 24 and 18 mm for these two grade bands respectively, is required to ensure only 20% steel in the carbonated concrete. Thus, the 40 mm minimum cover is generally sufficient for low grade concrete and is more than sufficient for higher grade concretes with respect to carbonation only.

Figure 5.77 shows the 80% confidence limit for the predicted carbonation depths of the three concrete grades in this locality. The confidence limits for Grade 20 – 25 and Grade 30 – 35, as well as Grade 30 – 35 and Grade 40 – 45 are well overlapped with each other respectively. This suggests that the predicted carbonation depths for these concrete grade bands are very similar. In contrast, the confidence limits for Grade 20 – 25 and Grade 40 – 45 do not have a large portion of overlapping, and this indicates that the predicted carbonation depths differ significantly.

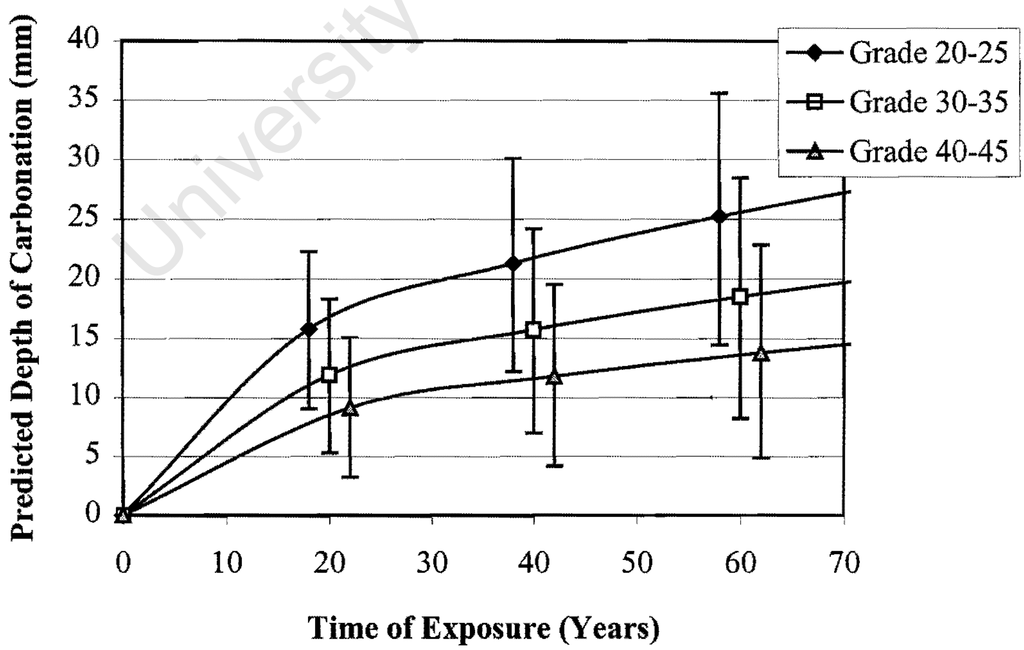


Figure 5.77: 80% Confidence limits for concretes (manufactured between 1970 and 1982) in Durban locality

5.6.3 Johannesburg Locality

Exposed and sheltered elements can be combined as one group as the carbonation rates for these two exposures with similar concrete grade (quality) are only marginally different. The percentile carbonation depths for two concrete strength grades, namely Grade 20 – 30 (includes Exposed Grade 20-30, Sheltered Grades 20-30 and 30-35) and Grade 35 (Exposed Grade 35) are shown in Figure 5.78 and 5.79.

Owing to the dry environment in the Johannesburg locality, the rate of carbonation is pronounced. For example, in order to have only 20% steel in the carbonated concrete for 50 years of exposure, minimum covers of 33 mm and 30 mm for Grade 20 – 30 and Grade 35 concretes respectively. It should be noted that although the risk of serious corrosion is low in this locality owing to the dry environment, sufficient cover should be provided. This is because if moisture is introduced to the structure (e.g. joint leakage) after depassivation (e.g. due to carbonation), extensive corrosion could then take place.

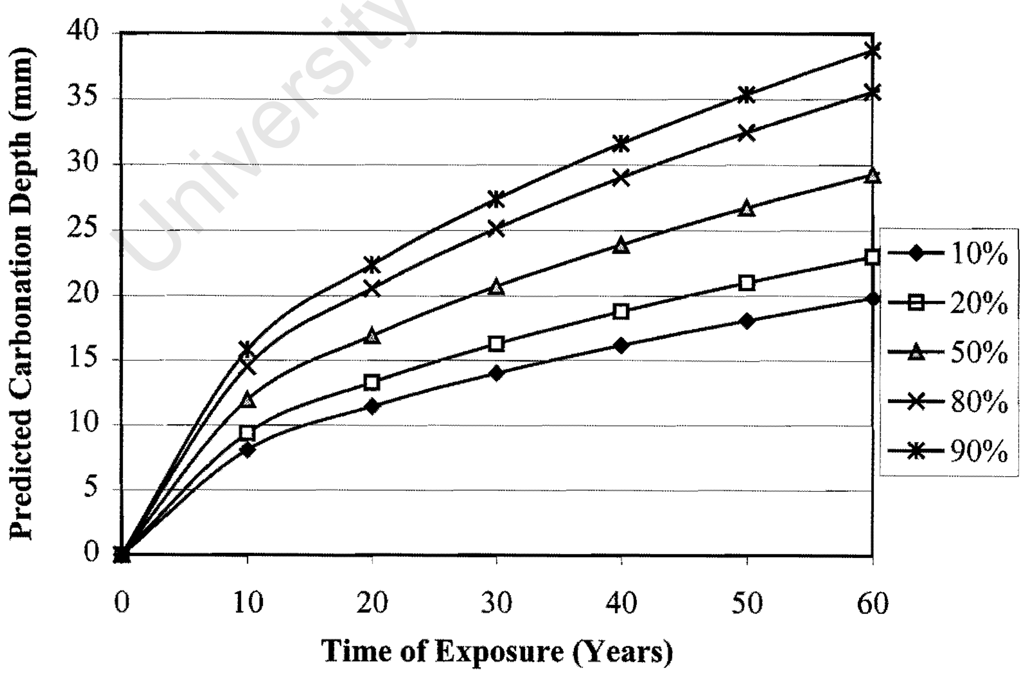


Figure 5.78: Selected percentile carbonation depths for Grade 20 – 30 concretes in Johannesburg locality

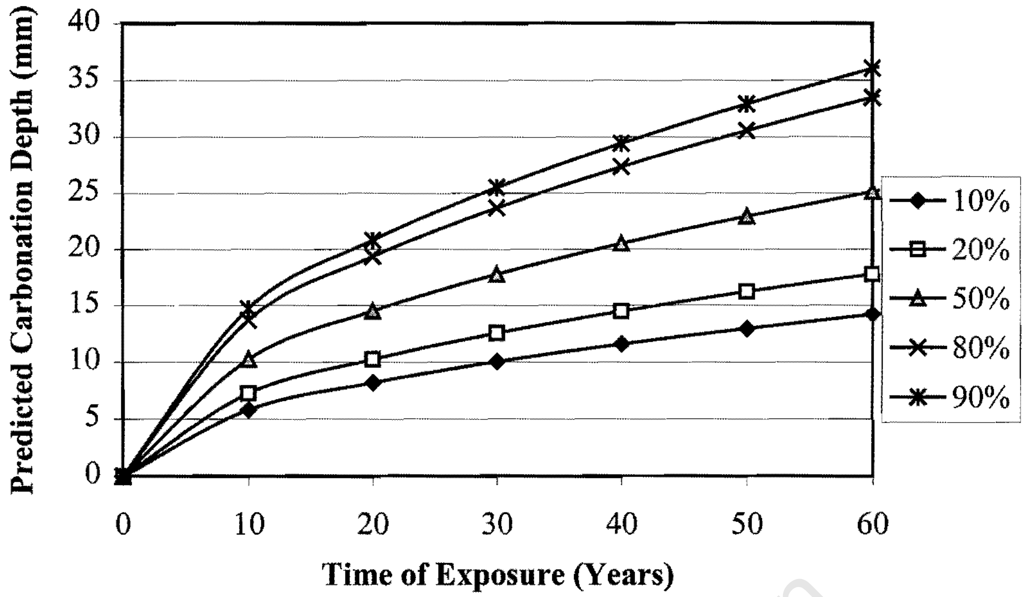


Figure 5.79: Selected percentile carbonation depths for exposed Grade 35 concretes in Johannesburg locality

It can be seen from the 80% confidence limits for these two concrete grades as shown in Figure 5.80 that these two concrete grades have very similar carbonation depths as a large portion of confidence limits overlaps with each other.

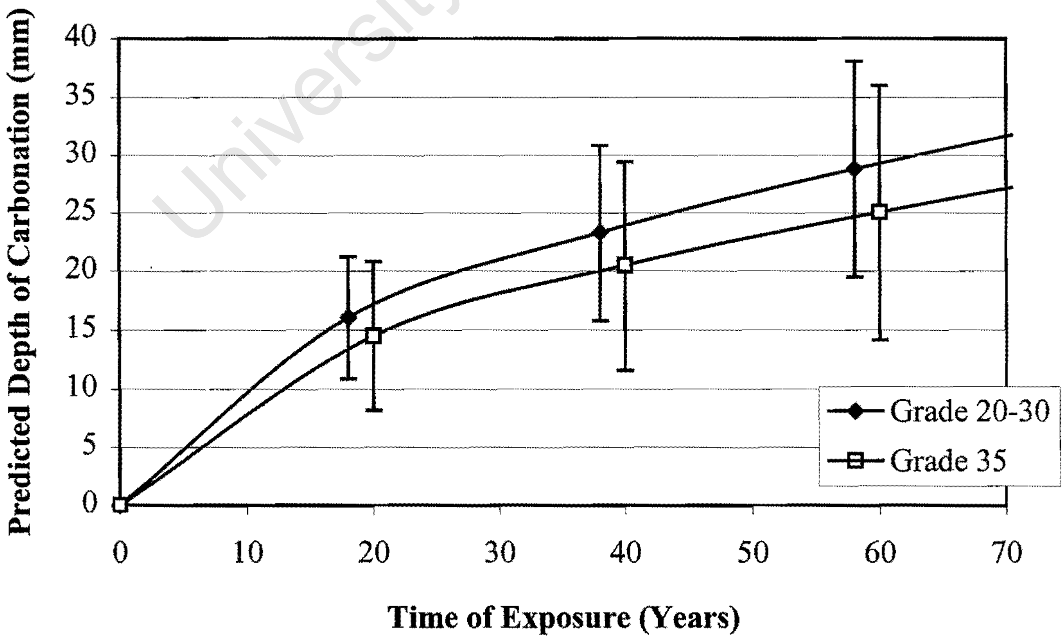


Figure 5.80: 80% Confidence limits for concretes in the Johannesburg locality

By looking at the 80% confidence limits for the concretes in the three localities, it may be argued that the concrete grade (quality) may not have a significant effect on the rate of carbonation since the majority of the 80% confidence limits for these grades overlap each other (such as those in the Johannesburg locality as shown in Figure 5.80) in the respective locality. However, the good overlapping of the confidence limits are due to the large difference between the 90th and 10th percentile carbonation depth values. This large difference was attributed to the high variability of the measured depth of carbonation from the in-situ bridge elements. In the next section, a brief discussion on the variability as well as the possible reasons for the cause of the carbonation depth gross outliers of the in-situ carbonation data will be provided, in order to understand the variability of the obtained field carbonation data.

5.7 Variability and Gross Outliers of the Carbonation Data

5.7.1 Variability of the Field Carbonation Data

The measured field carbonation data show a very wide scatter as illustrated previously, giving a large difference between the 90th and 10th percentile carbonation depth values. Despite the identified gross outliers which will be discussed later, the variability of these data, within the acceptable range (i.e. within two times the residual standard deviation), will now be discussed briefly. The observed high variability may be due to: the construction practice of the contractors, the climatic conditions during the early age of the bridges, and the orientation of the bridge elements from which the carbonation depth were measured.

(a) Construction Practice

Construction practice can be broadly defined by several processes, namely, materials batching, mixing, placing, compacting and curing. The differences in batch materials (such as different types of sand), and quantities (as the target strength for a given design concrete strength grade might vary, for example, according to contractors' preferences) can affect the rate of carbonation for two concretes with the same design grade.

In addition, during mixing and placing, air may be trapped in the cast elements and appear as air voids. These air voids can interconnect with capillary and gel pores in the mix and hence increase the permeability of the concrete, therefore, the rate of carbonation will also be increased. These air voids can be largely eliminated through adequate compaction. Since the carbonation data were measured from different in-service bridges, the degree of compaction may be different. If one bridge had a better compaction than another bridge, the former bridge would have a lower carbonation depth than the latter at the same time owing to a lower permeability.

The duration of curing can affect the rate of carbonation as it has a substantial influence of the permeability of the concrete especially in the cover zone. Proper curing allows the formation of hydration products through cement hydration. The products of hydration refine the pore structure and hence decrease the ease of carbon dioxide ingress through the concrete. The amount of hydration products increases with the duration of curing particularly in the early age of the concrete. Better-cured concrete should have a lower carbonation rate than poorly cured concrete with the same materials and under the same exposure conditions.

(b) Early Age Climatic Conditions

The carbonation data were measured from different in-service bridges which were constructed at different times (i.e. seasons), and the climatic conditions at the early ages were therefore not necessarily the same. According to Bakker (1988), if any in-situ concrete was exposed to rain during its early age or just after the obligatory curing period, this concrete is less permeable, due to the rain water providing an external source of moisture to promote further hydration particularly to the cover (near-surface) zone. In other words, if the bridges were completed in the season with high rainfall, the permeability and hence the depth of carbonation would be less than those bridges which were constructed in a dry, low rainfall season.

In addition, if the bridges were exposed to a relatively high temperature (for example, in summer), the moisture in the cover zone tends to egress to the surrounding atmosphere and hence the permeability in the cover zone is high owing to the lack of sufficient moisture to promote cement hydration and the formation of hydration products. Thus, depth of carbonation measured would be relatively higher than those bridges experiencing a relatively low temperature during and after the obligatory curing period.

(c) Orientation of the (Exposed) Elements

The carbonation data were measured in different elements which had different orientations, or facing directions. These elements, especially the exposed elements, with different orientations may be subject to different climatic conditions. For example, if an exposed element faces the same direction as the prevailing wind direction, this element is likely to be wetter than the elements which face the opposite direction during the high rainfall season in the Cape. Also, elements facing north (in the southern hemisphere), receive a longer duration of sunshine and are hence drier and warmer than the elements facing south. As noted previously, the wetter the element, the slower the rate of carbonation due to the slow carbon dioxide diffusion. In the analytical section of this thesis, the orientation of the elements was not considered, since further subdivision of the data would result in the reduction of the number of data for each concrete strength grade group, hence creating statistical inaccuracy.

The above reasons however, can help to account for the variability of the carbonation data. However, there are some data that had extreme carbonation depth values which differed markedly from the rest of the data set. Their existence may be due to reasons other than the ones above.

5.7.2 Possible Reasons for Carbonation Depth Gross Outliers

Several carbonation depth gross outliers were identified from the statistical analysis for all three localities in the respective groups of concrete grade (quality) and exposure conditions. These gross outliers are either substantially higher or lower than the rest of the data which were subjected to the same material and environmental conditions. In this section, three possible reasons for the existence of these outliers are listed:

(a) Presence of Cracks

The presence of cracks on an in-service structural element can be due to plastic shrinkage, drying shrinkage, thermal contraction and service loads. Through these cracks, carbon dioxide can proceed deep into the concrete in a relatively short period of time. This is one possible reason why some carbonation data may have much higher carbonation depths than the rest of the data of their respective groups.

(b) Localised High Moisture Content

Moore (2003) suggests that some (sheltered) bridge elements stay relatively wet for a long period of time. This is due to the leakage of joints. Elements affected include deck soffits, abutments and columns. Since the affected elements are wet (pores have a high moisture content or even saturated over a long period of time), the diffusion of carbon dioxide in these elements is thus very slow. Therefore, some carbonation data have very low carbonation depth values.

(c) Material Inhomogeneity

Concrete is made up of different materials such as cement, water and aggregates. The configuration of these materials, the distribution of voids/pores and aggregates which interact with different construction practice (such as compaction and curing) as listed in the previous section can affect the rate of carbonation and hence the depth of carbonation with time. An extreme combination of these factors can give extreme high and low carbonation depth values.

5.8 CONCLUDING SUMMARY

Two different statistical methods were employed and compared, in order to analyse the field carbonation data and hence to derive carbonation prediction models for Cape Peninsula, Durban and Johannesburg localities. The method of least squares was found to be a better method since it avoided the need to assign a non-zero "initial" point as well as the level of simplicity. Thus, the method of least squares was used to analyse the carbonation data.

However, since the data show a very wide scatter, the derivation of a carbonation prediction model based on these data relying entirely on statistical analysis is not adequate as many different models (with different k and n values) can fit the data equally well. Therefore, the scientific principle of diffusion, together with the understanding of the process of carbonation of field concrete and the climatic conditions of the localities were integrated with the statistical analysis in order to derive such prediction models.

In the Cape Peninsula locality, n was selected to be 0.4 (instead of the theoretical value of 0.5 under ideal diffusion conditions) due to the concretes being exposed to rain, the relatively high relative humidity (beyond the optimum ranges for carbonation) as well as the improvement of the pore structure with depth and time.

In Durban locality, n was also selected to be 0.4 for both exposed and sheltered elements. Although sheltered elements were sheltered from direct rain (not subject to wet and dry cycles), the near-surface moisture content for these two types of elements are similar owing to the short rainfall duration and high relative humidity in this locality. These climatic conditions can also explain the similarity of carbonation rates for these two types of elements (with the same concrete strength grade).

In Johannesburg locality, n was selected with a slightly larger value of 0.5. This is mainly because of the dry climatic conditions which promote rapid rates of carbonation. In addition, the carbonation rates for both exposed and sheltered elements are very similar, because of the short rainfall pattern and dry climate which cause the near-surface moisture content of the exposed elements to revert to the atmospheric relative humidity (similar to the sheltered elements) in a relatively short period of time.

According to the 80% confidence limits for these three localities, it seems that the concrete grade does not have a significant effect on the rate of carbonation. However, this is because of the high variability of the field carbonation data. The variability of the data is likely to be due to the variable construction practice such as degree of compaction and duration of curing, the early age climatic conditions that the bridges experienced, the orientation of the bridge elements, the presence of cracks, different moisture content of the elements as well as material inhomogeneity. It should be noted that the "extreme" combination of these factors can yield "extreme" carbonation depth values.

From the analysis of the data from Durban locality, there exist two different concrete population groups (1956 – 1964 and 1970 – 1982), which exhibit two different carbonation rates, even though they are of the same design concrete strength grade. The "old" population group had a substantially lower carbonation rate than the "modern" population group. This may be due to the fact that "modern" cements are ground finer and have a higher tricalcium silicate content, and hence a higher water/cement ratio can achieve a higher early strength. Based on these facts, the carbonation prediction models derived in this chapter can only predict the rate of carbonation for concretes produced in the same period as the construction periods of bridges. This is also true in the Cape Peninsula and Johannesburg localities and this issue will be discussed in the next chapter.

CHAPTER 6

USE OF OXYGEN PERMEABILITY INDEX (OPI) FOR CARBONATION PREDICTIONS:

INTRODUCTION AND PROPOSED FRAMEWORK

6.1 INTRODUCTION

Durability of reinforced concrete structures is a major concern for engineers in terms of designing and specifying the concrete mix as well as the depth of cover concrete. As mentioned in Chapters 2, premature deterioration of concrete can lead to serious aesthetic and structural consequences and considerable amounts of money are needed to repair and rehabilitate damaged concrete structures. There has been much research investigating the actual deterioration mechanisms which can occur in concrete.

One of the most common deterioration mechanisms of reinforced concrete is the corrosion of embedded steel reinforcement. As described in Chapters 2 and 3, the corrosion of the steel reinforcement may be caused by the process of carbonation of the cement hydration products. In order to assist in avoiding carbonation-induced corrosion, this thesis is concerned with predicting the rate and depth of the carbonation within concrete, so as to inform maintenance plans for existing structures, and also provide an adequate depth of cover concrete for future structures to protect the reinforcing steel from corroding within the design service life.

In Chapter 5, several such prediction models were derived for three different South African localities. The models were based on concrete strength grade (an overall concrete quality parameter). However, this may not be the most appropriate parameter to characterise the quality of the concrete cover zone where carbonation takes place. Therefore, another parameter which can assess the cover concrete quality needs to be sought. In addition, such a parameter should also be linked with the process of gaseous diffusion as the rate of carbonation is governed by the diffusion of carbon dioxide.

In this chapter, a possible approach to tackle this problem is described. The proposed approach is to make use of the Oxygen Permeability Index (OPI). A review of the OPI will be given, and the relationship between OPI and carbonation depth for the Cape Peninsula locality structures will be discussed. In addition, a framework for using OPI for carbonation prediction will be suggested.

6.2 DURABILITY INDEX TESTS

The control of the durability of reinforced concrete relies on the resistance of the cover concrete to the ingress of aggressive species such as carbon dioxide. Three durability index tests have been developed to index the resistance offered by concrete to different species based on their transport mechanism in concrete. These durability index tests are: the water sorptivity test, chloride conductivity test and oxygen permeability test. These tests measure a specific transport mechanism of the species.

Water sorptivity measures the absorption of water uni-directionally due to capillary action of the concrete pores. The rate of absorption depends on the pore geometry and the degree of saturation. This test is sensitive to the near surface transport properties and can be used as a tool to assess the curing of concrete. Detailed information related to this test can be found in Alexander et al (1999a) and (2001).

The Chloride Conductivity test aims to measure the resistance of the concrete (mainly marine concrete) to the diffusion of chloride ions. The test saturates the concrete with high concentration chloride solution under vacuum in order to achieve steady state conditions in a relatively short period of time. Information relating to this test can be found in Alexander et al (1999b).

The Oxygen Permeability Index test measures the permeation of fluid (i.e. oxygen) through concrete under an externally applied pressure. This test will be discussed in detail in this chapter as it can possibly be used as a tool to predict the depth of carbonation in concrete. This test may be suitable to predict the depth of carbonation because it can characterise the gaseous permeability of a concrete which is influenced mainly by the pore structure, whilst the depth of carbonation is governed by the physical nature of the pore geometry, size and interconnectedness as well as the chemical nature of the binders.

6.3 Philosophy of Oxygen Permeability Index (OPI)

Current Codes of Practice around the world have durability specifications (for example, SABS 0100). These codes are generally prescriptive, that is, they prescribe the maximum water/binder ratio, the curing duration, minimum cement content as well as minimum cover depths. However, they generally do not take binder type into consideration and do not clarify what sort of curing regime should be used within the specified curing period.

Until now, compressive strength has been a commonly used parameter to assess the durability of concrete, which includes durability against carbonation-induced corrosion. The reason for this is because of its ease of measurement as well as the fact that it can give a crude idea of the pore structure of the concrete from the fully cured cubes. However, this parameter merely reflects the pore structure of the fully cured material, and therefore it is not adequate to ensure the durability of the in-situ reinforced concrete structure against carbonation. In addition, compressive strength is a measure of the average property of concrete in relation to the applied compressive stress. Although compressive strength can be a very crude measure of the degree of porosity and interconnectedness of pores within concrete as a whole, it is still inadequate to measure the permeation of carbon dioxide through concrete.

The protection of the embedded steel reinforcement against carbonation-induced corrosion is mainly offered by the cover concrete. In other words, a parameter which can be related to the diffusion of carbon dioxide through the cover concrete would be a sound and reliable parameter to predict and therefore help to avoid carbonation-induced corrosion.

The Oxygen Permeability Index (OPI) is an index which can characterise properties such as degree of porosity and interconnectedness of pores of cover concrete in relation to gas permeability. It should be noted that, although the ingress of carbon dioxide is a diffusion process (driven by concentration gradient), the ease/rate of this diffusion through concrete is influenced by the inherent permeability (an indication of degree of porosity and pore interconnectedness). Therefore, a measure of concrete gaseous permeability might provide an index of gaseous diffusion through concrete. Below is a brief description of the equipment, test procedures, and advantages as well as a discussion of the factors that can affect the Oxygen Permeability Index (OPI).

6.4 OXYGEN PERMEABILITY INDEX TEST

6.4.1 Test Description

The detailed description of the procedures of the OPI test can be found in Alexander et al (1999a). Briefly, concrete specimens (68 mm diameter and 25 mm thick) are dried in an oven at 50°C for seven days. After that, the specimens are placed into a silicone rubber collar and positioned in the permeameter as shown in Figure 6.1. The permeameter is connected to the digital converter and data-logging computer for data recording.

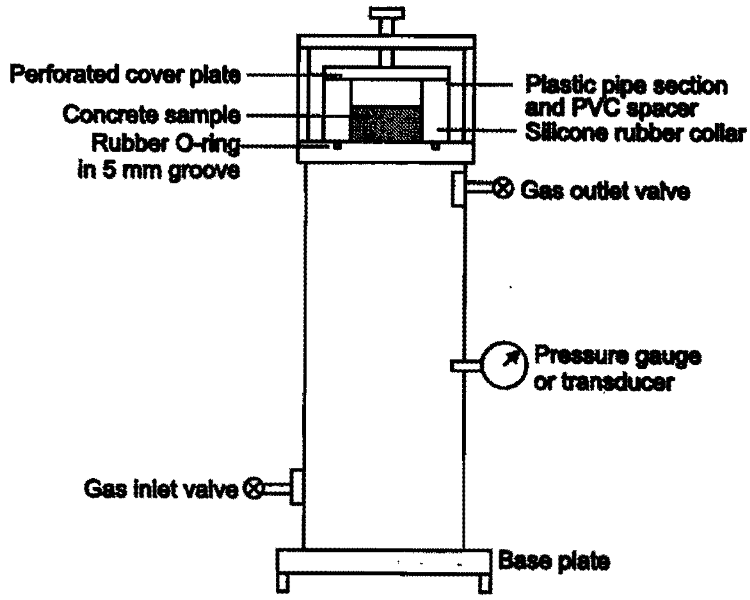


Figure 6.1: Permeameter for Oxygen Permeability Index (OPI) test (Alexander et al (1999a)).

The permeameter is pressurized by oxygen at 100 kPa and the digital converter with the data-logging computer records the pressure decay with time as oxygen permeates through the concrete specimen. The graph plotting the natural log (ln) of the ratio of initial pressure to decaying pressure against time can then be plotted. Such a graph is shown below in Figure 6.2 for demonstration purposes.

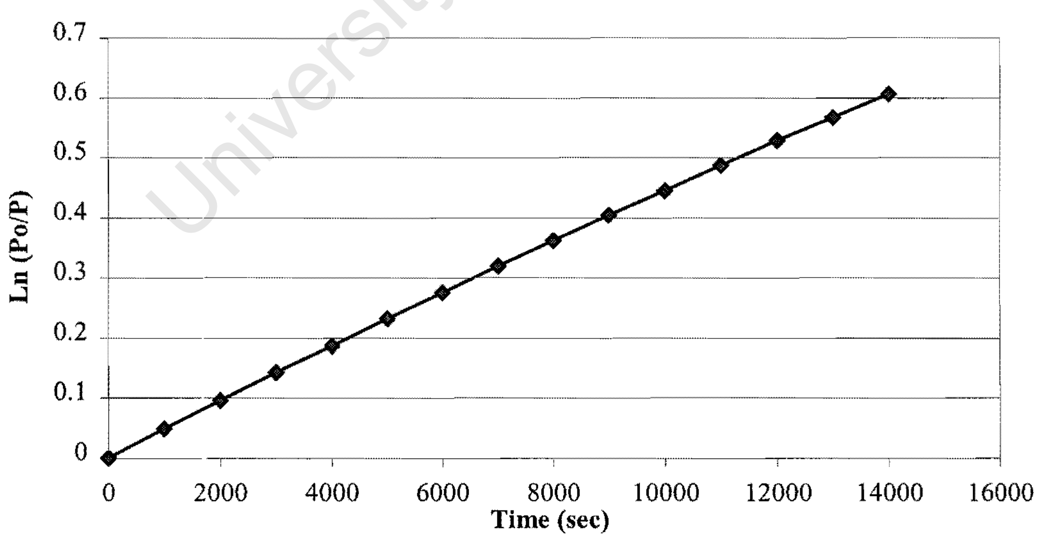


Figure 6.2: Typical OPI Test results

By doing linear regression analysis of the graph (as in Figure 6.2), the coefficient of permeability (k) can be determined by Equation 6.1. The derivation of Equation 6.1 can be found in Alexander et al (2001).

$$k = \frac{\omega V g d z}{R A \vartheta} \qquad (6.1)$$

where

k = coefficient of permeability of test specimen (m/s)

ω = molecular mass of oxygen (O_2) = 32 g/moles

V = volume of oxygen under pressure in the permeameter (m^3)

g = acceleration due to gravity (m/s^2)

R = universal gas constant = 8.313 (Nm/Kmol)

A = cross sectional area of the specimen

d = specimen thickness (m)

ϑ = absolute temperature (K)

z = slope of the line determined from the regression analysis (s^{-1})

The Oxygen Permeability Index (OPI) of the specimen is given by the negative log of k, i.e.:

$$OPI = -\log_{10}(k) \qquad (6.2)$$

OPI is defined as the negative log of k due to practical considerations since k has a very large negative exponent.

It should be noted that the higher the OPI, the less permeable the specimen to oxygen permeation. That is to say, the higher the OPI, the greater the resistance to gaseous ingress.

6.4.2 Advantages of the Test

The Oxygen Permeability Index (OPI) test has advantages in regard to the manufacture of the apparatus, and the ease of the operation of the test for both laboratory and site uses (Ballim (1991)). This test is thus suitable for practical use.

The use of a falling head permeameter can reduce the cost of manufacture of the permeameter in comparison with a constant head permeameter. This is because the falling head test does not involve the monitoring of the volume and the flow rate of oxygen gas on the downstream side of the concrete specimen. This simplifies the manufacture of the permeameter, hence leading to a lower cost of manufacture than that of a constant head permeameter. Apart from that, the operation of the test is also easier than the conventional constant head test since the pressure of the oxygen gas is only recorded on the upstream side of the concrete specimen.

Other advantages are the relatively simple skills required, the suitability of testing different types of concrete specimens with a wide range of quality, and the relatively short duration of the test period (typically 2 – 6 hours). All these advantages enhance the practical use of the test.

6.5 OTHER ASPECTS OF OPI TEST

6.5.1 Number of Specimens Required

For each mix, four specimens (68 mm diameter and 25 mm thick) are preferable to three specimens in order to determine the OPI. The reported OPI is the negative log of the average of the coefficients of permeability of the specimens (Alexander (2001)), i.e.

$$OPI = -\log_{10}\left[\frac{(k_1 + k_2 + ... + k_n)}{n}\right] \text{ (for n samples, where } n \geq 4) \qquad (6.3)$$

Three specimens are enough to produce a mean value, but the additional specimen is for substitution in case of a failed test. The need for retesting will be dealt with in the following subsection.

6.5.2 Validity of Test

For a "valid" OPI test, it is generally regarded that the coefficient of correlation for the natural log of the ratio of pressures to time relationship needs to be greater than 0.99. This helps to ensure that data collection and recording is adequate and that nothing has gone wrong during the test such as the development of a gas leak.

Alexander (2001) explained the reasons why a specimen sometimes does not achieve the 0.99 correlation coefficient requirement:

- Leakage of oxygen through the test rig during the test
- Badly cracked sample or sample with large voids on its test surface
- Inaccurate pressure and time readings
- Reduction of sealing pressure offered by the rubber collar to the specimen due to the creep effect under load during the test

6.6 FACTORS AFFECTING OXYGEN PERMEABILITY INDEX (OPI)

6.6.1 Materials

OPI is sensitive to water/binder ratio and, to a lesser extent, binder type. Both water/binder ratio and binder type have important effects on the pore structure of the concrete. As noted in section 3.3.2 (a), the pore structure of concrete can affect the permeation of carbon dioxide and hence influence the depth of carbonation. Table 6.1 shows the effects of different water/binder ratio and binder types on OPI.

Table 6.1: Effects of water/binder ratio and binder types on OPI at 28 days given by Concur Spreadsheet (available at UCT Website, http://www.civil.uct.ac.za/research/materials/concur.xls)

Binder Type	Water/Binder Ratio	OPI (log scale)
100%OPC	0.5	10.13
	0.7	9.67
70% OPC / 30% FA	0.5	10.32
	0.7	9.99
50%OPC / 50% Slag	0.5	9.86
	0.7	9.34
90%OPC / 10% CSF	0.5	10.44
	0.7	10.10

Note: OPC means Ordinary Portland cement, FA for Fly Ash, Slag refers to Ground Granulated Blastfurnance Slag and CSF for Condensed Silica Fume

From Table 6.1, OPI decreases with increasing water/binder ratio for each binder type under the same curing regime of 28 days wet curing at 23°C. Porosity and permeability decreases with decreasing water/binder ratio. In comparison with different binder types of the same water/binder ratio in Table 6.1, CSF concrete has the highest OPI, implying that CSF concrete is less permeable.

Since OPI is sensitive to both water/binder ratio and type of binder, it may therefore be a good tool in material selection during the design stage of concrete structures.

6.6.2 Construction Practice

Construction practice here refers to the degree of curing as this can affect the degree of hydration of cement and hence the porosity and permeability of concrete. Although placing, compaction, control of bleeding, and temperature also have important effects, they are not considered here as no reliable or quantifiable information is available from in-situ concrete. Alexander (1997) showed the effect of three different curing regimes on the effect of OPI as shown in Figure 6.3. "Dry cured" means no curing or air curing, "moist cured" refers to typical good site curing and "wet cured" represents continuous supply of water.

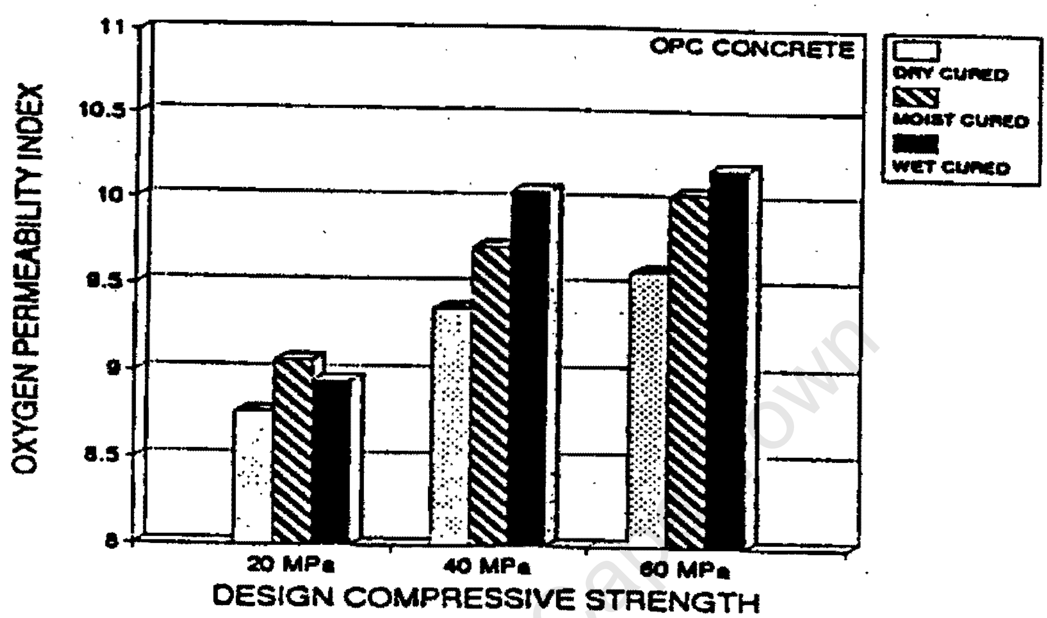


Figure 6.3: Effects of different curing regimes on OPI (Alexander (1997)).

Generally speaking, wet cured samples exhibit a higher OPI values for Grade 40 and 60 MPa concretes. This is because wet cured samples have the highest degree of hydration and hence the lowest porosity which can account for the low permeability. For Grade 20 concretes, curing has a lesser effect, due probably to the fact that the pore structure of such low-grade concrete remains relatively open irrespective of different curing regimes.

Since OPI is sensitive to the effects shown above, this is useful as an indication of whether site concrete is properly cured. Following the same argument, OPI can also indicate the degree of compaction, as adequate compaction can diminish permeability of concrete by eliminating voids such as air voids.

6.7 PROPOSED FRAMEWORK FOR THE USE OF OPI FOR CARBONATION PREDICTION

6.7.1 Background

It has been mentioned that compressive strength is not a good parameter to predict the depth of carbonation as it merely measures a bulk property of concrete whilst carbonation of concrete occurs in the concrete cover. In Chapter 5, the derived carbonation prediction models were based on compressive strength owing to the fact that compressive strength is by far the most common parameter to characterise the quality of concrete, and also no early age (say 28 day OPI) measurements were made for those bridges. It should be noted that in order to obtain a confident prediction of the depth of carbonation, a parameter which can measure the quality of, in particular, the concrete cover is required.

The question might be asked: can OPI be used as a tool to predict carbonation depth? To answer this question, one should clearly understand what OPI really means. OPI is an index indicating the gaseous permeability (which is highly dependent on the microstructure and pore structure) of concrete. A porous concrete which has a low OPI value denotes a high rate of gas "penetrability" through the concrete. Since this index may be taken as a measure of gas penetrability, it may be useful to predict rate of carbonation.

6.7.2 Previous Work Done on Carbonation Predictions Using OPI

Mackechnie (1999) has done a correlation between OPI values at 28 days of age and carbonation depths for the periods of 1, 4 and 6 years of outdoor exposure outside the Laboratory of the University of Cape Town. Table 6.2 shows his results and **Figure 6.4 – 6.6** show the correlations.

Table 6.2: Concrete mixes and results (Mackechnie (1999))

Binder Type	Grade (MPa)	w/b ratio	Initial Curing	OPI (28 days)	Carbonation Depth (mm) at		
					1 year	4 years	6 years
Ordinary Portland Cement	20	0.83	Moist	9.07	7.5	13.0	14.0
			Dry	8.77	8.5	14.0	15.5
	40	0.56	Moist	9.73	4.5	5.0	6.5
			Dry	9.37	5.5	6.0	7.5
	60	0.38	Moist	10.05	1.0	1.0	1.0
			Dry	9.59	2.0	2.0	2.5
30% Fly Ash	20	0.71	Moist	8.60	10.5	13.0	18.5
			Dry	8.37	11.5	17.0	20.5
	40	0.46	Moist	9.83	4.5	5.0	7.5
			Dry	9.22	5.5	6.0	8.0
	60	0.34	Moist	10.24	1.5	1.5	1.5
			Dry	9.78	2.5	2.0	2.5
50% Blastfurnace Slag	20	0.80	Moist	8.94	11.5	15.0	19.0
			Dry	8.32	14.0	20.0	21.0
	40	0.51	Moist	9.73	4.0	6.0	8.0
			Dry	8.83	9.0	9.0	11.5
	60	0.35	Moist	10.19	2.0	2.0	2.0
			Dry	9.94	3.0	3.0	3.5

Three types of binders were used, namely, 100% Ordinary Portland Cement (OPC), Fly Ash (FA) with 30% cement replacement level and 50% Blastfurnace Slag (SL). Two different curing regimes were employed. One was moist curing for seven days, denoted "Moist", and the other was dry curing for seven days, "Dry". These two different curing regimes presumably represent good and poor site practice (details and comments were given in section 5.2.6 (b)). Regarding OPI and curing regime, moist cured samples always have higher OPI values due to the more refined pore structure which can hinder gas passage.

From Figures 6.4 to 6.6, there is a clear trend (also reflected by high coefficient of correlation, R^2 values) that the carbonation depth decreases with increasing OPI value at the same age which agrees with the effects of the pore structure of the concrete on the process of carbonation.

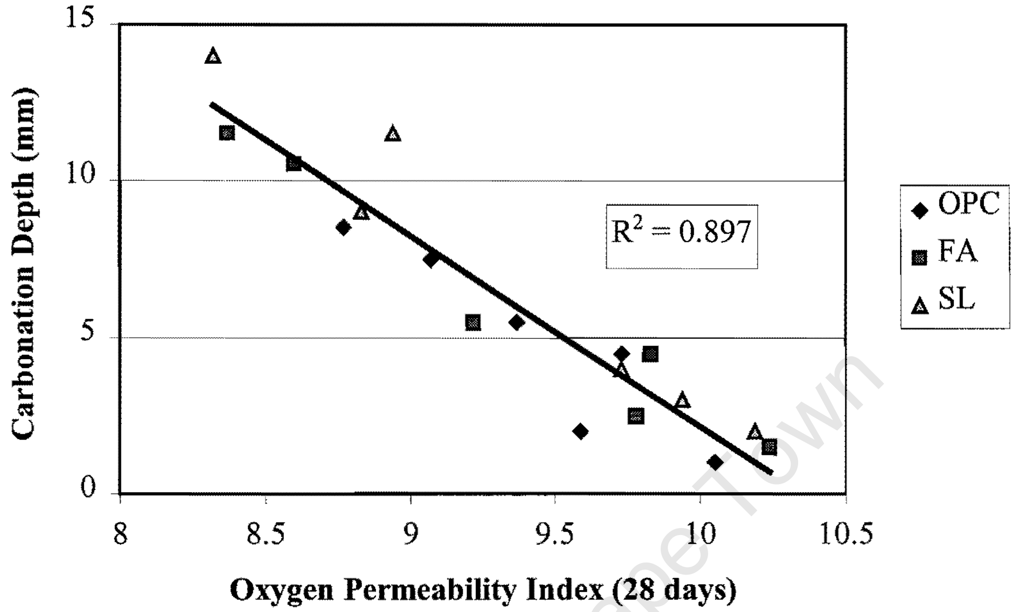


Figure 6.4: Carbonation depth vs OPI after 1 year (Mackechnie (1999))

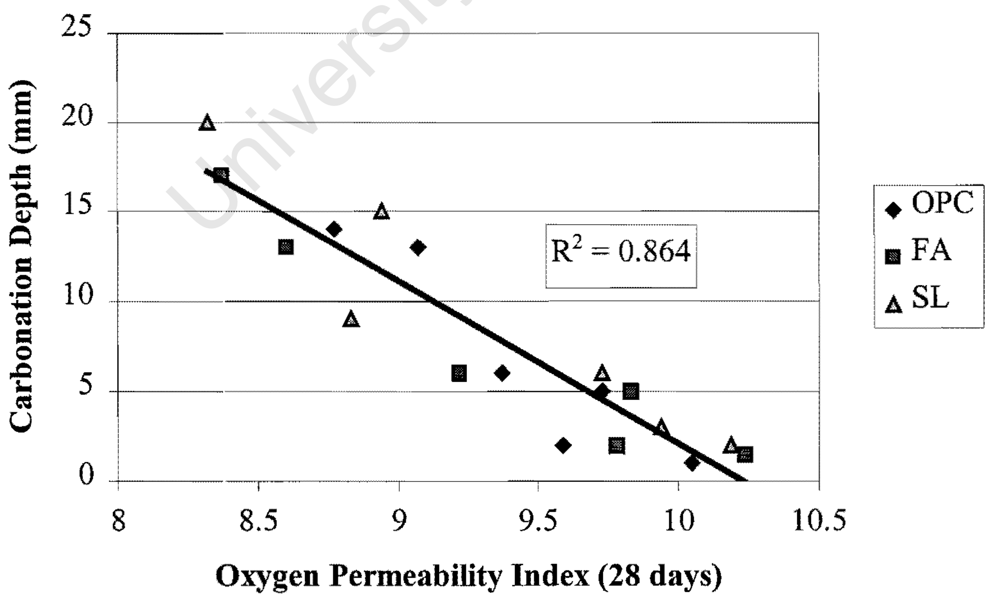


Figure 6.5: Carbonation depth vs OPI after 4 years (Mackechnie (1999))

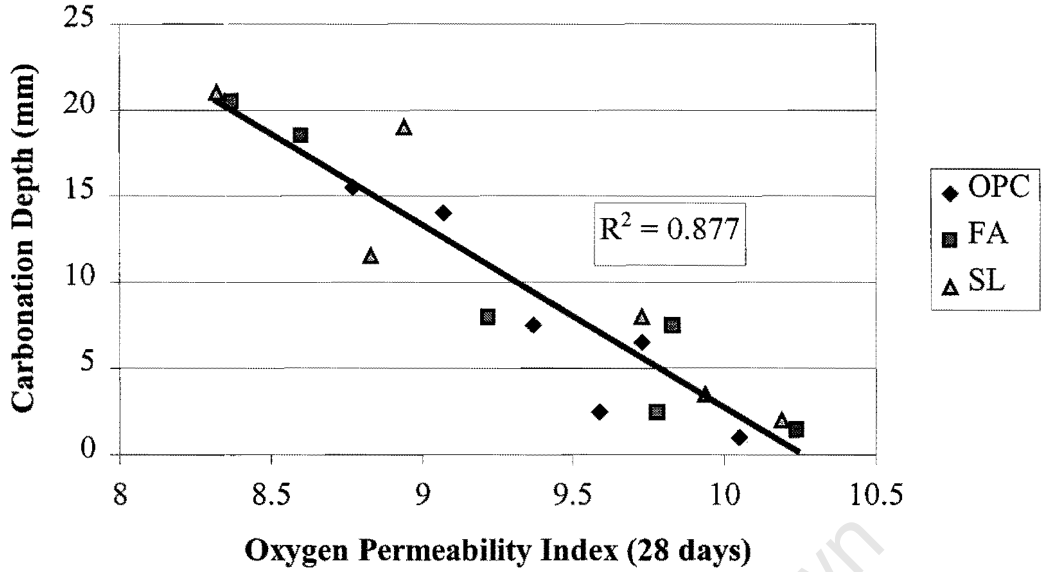


Figure 6.6: Carbonation depth vs OPI after 6 years (Mackechnie (1999))

In addition, these figures suggest that generally speaking, different binder types with similar OPI values yield similar carbonation depth. This means OPC, FA and Slag concretes with similar OPI values offer approximately the same resistance to carbonation. This may suggest that carbonation depth will be similar for these types of binder, provided the concrete can achieve the same OPI value. However, further work should be done in regard to this finding.

Mackechnie used the above results to construct a carbonation prediction chart using OPI for 10, 25 and 50 years exposure to the Cape Peninsula locality, as shown in Figure 6.7. However, Figure 6.7 is based on limited laboratory concrete specimens exposed to one local environmental condition outside the laboratory of the University of Cape Town as described in section 5.2.6 (b). This figure might be improved by gathering more in-situ carbonation data from more locations within the Cape Peninsula locality, in order to make allowances for the influences of different local environmental conditions on the rate of carbonation.

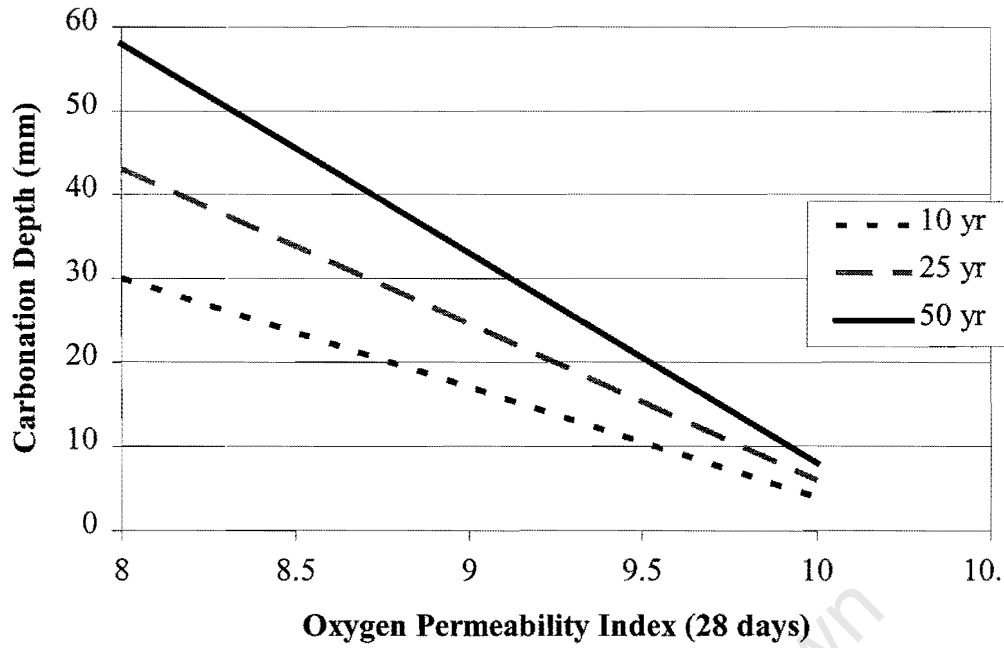


Figure 6.7: Predictions based on OPI at 28 days using carbonation equation, $d_c = kt^{0.4}$ (Mackechnie (1999)).

Considerable bridge data were obtained as presented in Chapter 4. These data were subjected to different local environmental conditions within their localities. A proposed framework for the use of OPI for carbonation prediction exploiting these data will be proposed.

6.7.3 Framework for Carbonation Prediction Using OPI

After the discussion of the philosophy, testing procedures and the merits of OPI test, and the clear correlation with carbonation depth as reflected by the short term carbonation results, a further investigation into the correlation of OPI with the (long-term) in-situ carbonation data as well as the possibility of using 28 day OPI as a carbonation prediction tool will be presented in this section.

Figure 6.8 shows a schematic proposed carbonation prediction chart which can be obtained by the procedures outlined in the proposed framework.

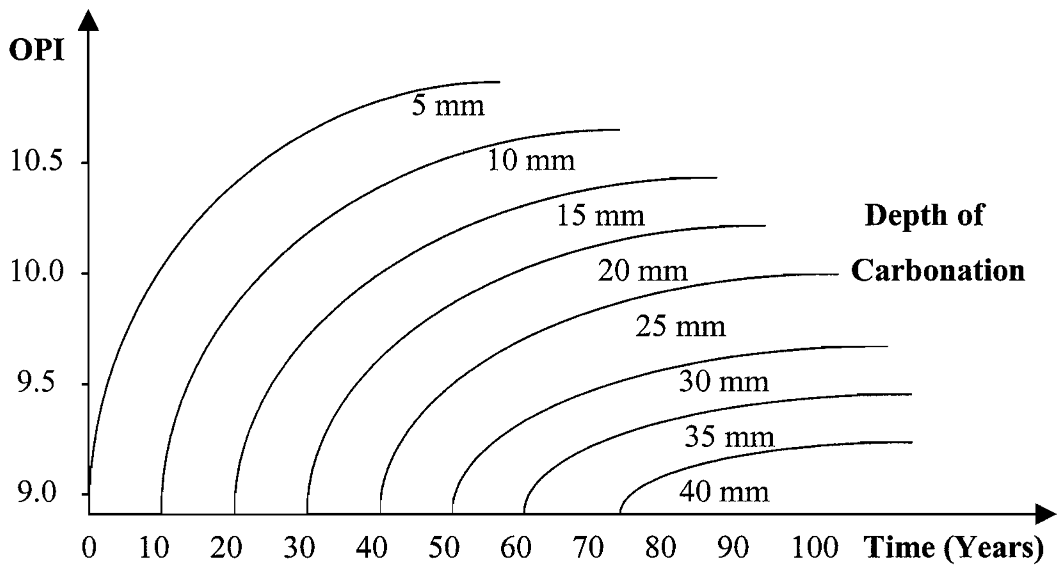


Figure 6.8: Schematic proposed carbonation prediction chart using OPI at 28 days

Since the OPI test was only developed in the 1990s, no early age OPI was measured for the bridges that were studied in the Cape Peninsula locality. Although the majority of the inferred compressive strengths at 28 days and water/cement ratio as well as the mature (later age) OPI of the core samples for this locality are known, this still cannot lead to the estimation of the 28 day OPI. This aspect will be explained in section 6.7.3 (b). Thus, the relationship between measured mature OPI and carbonation depth is studied instead. On the other hand, the carbonation data from Durban and Johannesburg localities could not be studied because only the design concrete strength grade was known.

Hence, only the bridge data from the Cape Peninsula locality will be used in this proposed framework. Table 6.2 shows the measured mature OPI for the carbonation data from Cape Peninsula locality only, and all necessary information for the attempt to estimate 28 day OPI. The detailed explanation for this table is given in the following section. Information for the data such as names of bridges can be found in Table 4.5.

Table 6.3: Measured mature and estimated OPI for the in-situ carbonation data (exposed concrete elements) from the Cape Peninsula locality

Age (t) (Years)	Strength at 28 days (MPa)	Inferred w/c	Measured Mature OPI	Mean[Ψ] Depth (mm)	Estimated OPI at 28 days	Measured d_c (mm)	k ($mm/yr^{0.4}$)
11	***60***	***0.40***	-	-	***10.05***	***5***	***1.92***
11	***60****	***0.40***	***10.1***	***26***	***10.05***	***11***	***4.22***
15	49.4	0.45	-	-	9.95	7	2.37
15	49.4*	0.45*	-	-	9.95	7	2.37
20	44.4*	0.51*	10.01	24	9.85	4	1.21
20	44.4	0.51	-		9.85	5	1.51
20	***55.5***	***0.43***	-		***10.01***	***9***	***2.72***
20	***55.5****	***0.43****	***8.59***	***25***	***10.01***	***8***	***2.41***
22	45*	0.49	10.32	20	9.88	8	2.32
22	45	0.49	-	-	9.88	8	2.32
22	**41.6***	**0.52***	**10.02**	**30**	**9.82**	**15**	**4.36**
22	**41.6**	**0.52**	-	-	**9.82**	**18**	**5.23**
33	39.4	0.54	8.51	29	9.77	8	1.98
33	32.2	0.63	-	-	9.54	10	2.47
33	**32.2***	**0.63***	**8.77**	**30**	**9.54**	**18**	**4.44**
33	40.5	0.53	-	-	9.79	8	1.98
33	40.5*	0.53	9.05	20	9.79	9	2.22
33	39.2*	0.55	8.83	55	9.75	5	1.23
33	39.2	0.55	-	-	9.75	6	1.48
33	39.2*	0.55*	9.89	42	9.75	9	2.22
33	27.7*	0.68	9.57	50	9.37	17	4.20
33	27.7	0.68	-	-	9.37	10	2.47
33	48.8	0.45	-	-	9.95	13	3.21
33	**48.8***	**0.45***	**8.87**	**40**	**9.95**	**19**	**4.69**
17	46	0.49	-	-	9.89	8	2.58
17	46*	0.49*	9.39	21	9.89	7	2.25
17	34*	0.63*	9.51	15	9.63	4	1.29
17	34	0.63	-	-	9.63	8	2.58
17	43.8*	0.51*	9.44	52	9.85	5	1.61
17	43.8	0.51	-	-	9.85	4	1.29
17	40*	0.56	10.37	19	9.77	4	1.29
17	40*	0.56*	-	-	9.77	4	1.29
17	43.3	0.51	-	-	9.84	9	2.90
17	43.3*	0.51*	9.96	54	9.84	10	3.22
28	***60.5***	***0.36***	-	-	***10.06***	***8***	***2.11***
34	36.1	0.58	-	-	9.67	9	2.20
34	36.1*	0.58*	8.36	25	9.67	10	2.44
34	38.3	0.56	-	-	9.74	11	2.68
34	38.3*	0.56*	7.89	29	9.74	15	3.66
34	35*	0.59*	9.56	45	9.65	6	1.46
40	40*	0.54*	9.51	28	9.77	13	2.97
40	**30**	**0.65**	-	-	**9.48**	**40**	**9.15**
40	30*	0.65*	8.89	35	9.48	23	5.26
40	36.9	0.57	-	-	9.72	16	3.66

Table 6.3 (Con't)

Age (t) (Years)	Strength at 28 days (MPa)	Inferred w/c	Measured Mature OPI	Mean[Ψ] Depth (mm)	Estimated OPI at 28 days	Measured d_c (mm)	k ($mm/yr^{0.4}$)
41	41.6	0.52	-	-	9.82	7	1.58
42	**34.4**	**0.60**	-	-	**9.63**	**20**	**4.48**
42	23.1	0.77	-	-	9.03	27	6.05
42	30.8	0.64	-	-	9.51	16	3.59
42	**30***	**0.65***	-	-	**9.48**	**56**	**12.56**
42	30	0.65	-	-	9.48	26	5.83
43	39.4	0.54	-	-	9.77	12	2.67
43	**39.4***	**0.54**	**8.89**	**20**	**9.77**	**20**	**4.44**
45	38.3	0.56	-	-	9.74	6	1.31
45	38.3*	0.56	9.23	30	9.74	17	3.71
45	26.1	0.71	-	-	9.29	25	5.45
45	30*	0.65	-	-	9.48	8	1.75
45	30*	0.65*	8.95	48	9.48	7	1.53
47	22.5	0.78	-	-	9.00	9	1.93
47	30*	0.65*	9.15	32	9.48	18	3.86
47	30*	0.65*	-	-	9.48	10	2.14
47	30*	0.65*	9.29	38	9.48	21	4.50
67	31.1	0.64	-	-	9.51	11	2.05
67	30*	0.65	-	-	9.48	19	3.53
67	30*	0.65*	-	-	9.48	22	4.09
42	33.3	0.61	-	-	9.60	12	2.69
42	33.3*	0.61*	8.92	38	9.60	17	3.81
42	36.9	0.57	-	-	9.72	7	1.57
42	36.9*	0.57*	9.15	30	9.72	11	2.47
16	42.5	0.53	-	-	9.84	4	1.32
16	32.2	0.64	-	-	9.54	7	2.31
25	35.6*	0.58*	-	-	9.67	4	1.10
25	35.6	0.58	-	-	9.67	3	0.83
44	30.8*	0.64*	9.97	26	9.51	12	2.64
44	30.8	0.64	-	-	9.51	13	2.86
75	30*	0.65*	-	-	9.48	13	2.31
76	30*	0.65*	-	-	9.48	12	2.12

Note: Results in bold and italics indicate no statistical analysis employed due to their inferred 28 day compressive strength > 50 MPa

Results in bold only represent d_c gross outliers based on Method of Least Squares

Ψ Mean depth of OPI sample – see Figure 6.9

* refers to assumed value

"– " means not measured

The estimated OPI at 28 days is to be treated with caution (due to the change in cement properties) – see later section

(a) Measured Mature OPI

- Normalisation of Carbonation Depth

In Table 6.2, the columns of "Age" and "Strength at 28 days" refer to the age of the bridge that the core samples were extracted from and the equivalent 100 mm cube compressive strengths at 28 days respectively. The assessment of the equivalent cube compressive strength can be found in section 5.2.4 based on the chart given in Figure 5.5. The "inferred w/c" is the inferred water/cement ratios for the core samples, also based on Figure 5.5.

The "Measured Mature OPI" is the OPI measured from the OPI test specimen at the time of measuring the depth of carbonation (i.e. at the given "Age"). The position of this test specimen is characterised by the mean depth measured from the surface of a core (see Figure 6.9) as recorded in the "Mean Depth" column in Table 6.3.

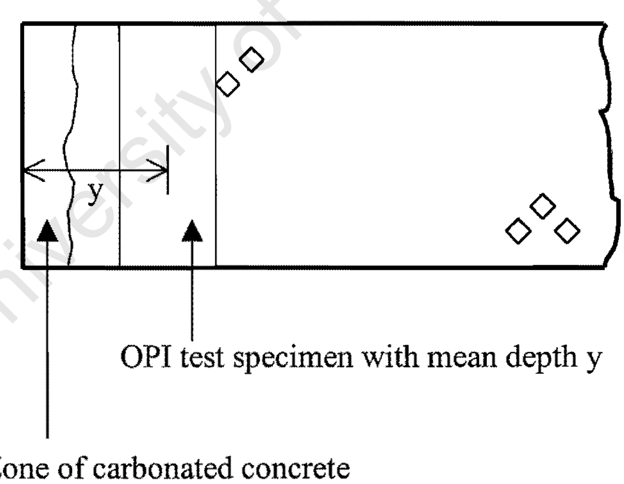


Figure 6.9: Position of the OPI test specimen of a core sample

Values of the "Estimated OPI at 28 days" should be treated with caution, as will be explained later. The "measured d_c" is the carbonation depth measured at the given "Age".

The "k" is the carbonation coefficient yielded by:

$$k = \frac{\text{Measured } d_c}{t^n} \qquad (6.4)$$

where: k is the individual carbonation coefficient in mm/year$^{0.4}$

Measured d_c is the carbonation depth measured from the core sample

t is the age of the bridge in years

n is the power series constant which equals 0.4 (based on exposed elements) for Cape Peninsula locality obtained from section 5.2.6 (c)

This k is needed for the comparison of the carbonation depths yielded by different measured mature OPI values. This is because carbonation depth increases with time. Thus in order to have a meaningful comparison between depths of carbonation yielded by different OPIs, a normalised depth of carbonation at a specific age should be used. For the purpose of normalising the depth of carbonation, the carbonation coefficient, k (i.e. carbonation rate) should be obtained for each data point using equation (6.4).

The depth of carbonation for each data point can then be normalised at a common age of, say, 50 years, by:

$$\text{Normalised } d_c \text{ at 50 years} = kt^n \qquad (6.5)$$

where: d_c is depth of carbonation

k is given by equation (6.4)

t equals to 50 years in this selected age

n equals to 0.4 for Cape Peninsula locality

- Normalised Carbonation Depth vs. Mature OPI

The correlation of measured mature OPI (with mean depths for the sample of less than or equal to 30 mm) and the normalised depth of carbonation at 50 years is shown in Figures 6.10 and 6.11 below. Measured mature OPI values only up to the mean depth of 30 mm are included, that is for sample boundaries between the depth of approximately 17 and 43 mm, because this depth range is adjacent to the carbonated concrete zone. On the other hand, specimens beyond the mean depth of 30 mm would tend to be rather remote from the region where carbonation takes place. Figure 6.10 contains the carbonation depth gross outliers which were identified by the Method of Least Squares from section 5.2.6 (c) for n equals 0.4, whilst Figure 6.11 shows the correlation after the elimination of all gross outliers.

It can be seen that there is a not a strong correlation between the normalised carbonation depth at 50 years and measured mature OPI. The normalised carbonation depths at 50 years are generally quite low, in the region of between 5 and 20 mm for OPI varying from 8 to 10.5. Based on Mackechnie's (1999) findings, clear linear trends exist, as shown in Figures 6.4 – 6.6. Therefore, a decision of a linear trend is made as the trend for carbonation depth against OPI.

It is useful to compare the linear trend lines given by the in-situ carbonation data in Figure 6.11 with the one given by Mackechnie. Such comparison is shown in Figure 6.12.

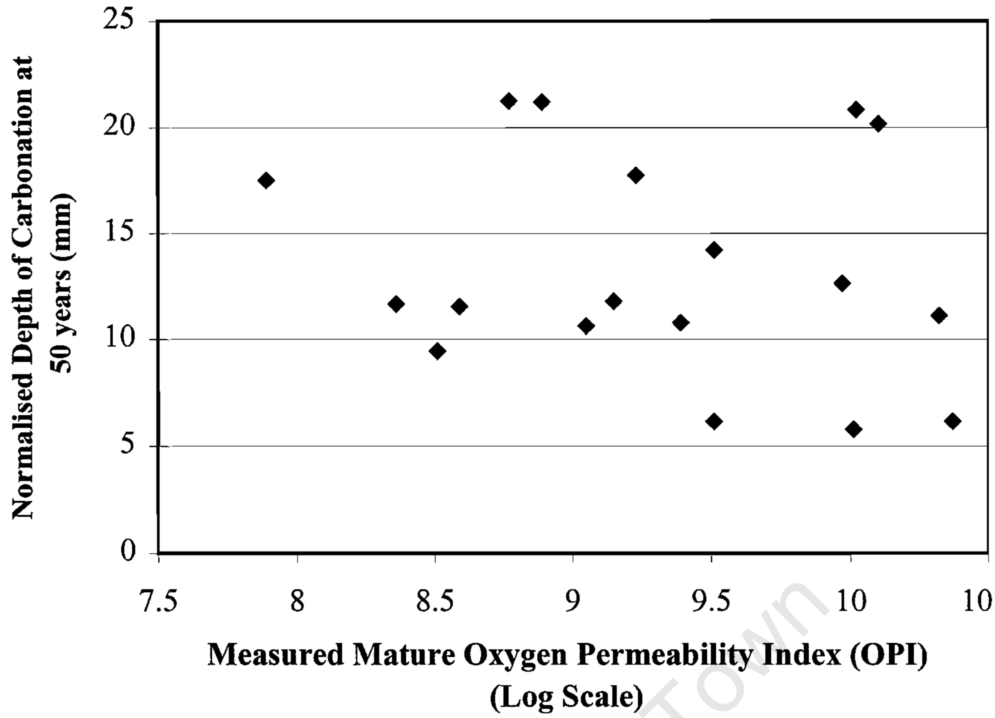


Figure 6.10: Trend of normalised carbonation depth and measured mature OPI (with all results including carbonation depth gross outliers)

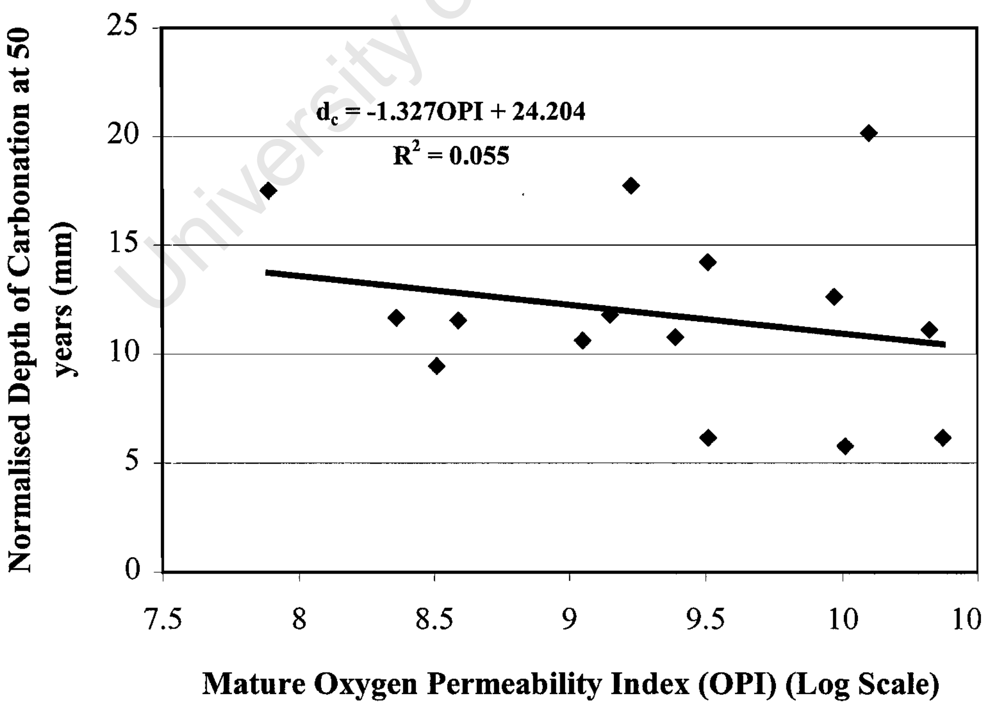


Figure 6.11: Trend of normalised carbonation depth and measured mature OPI (without carbonation depth gross outliers, 3 No.)

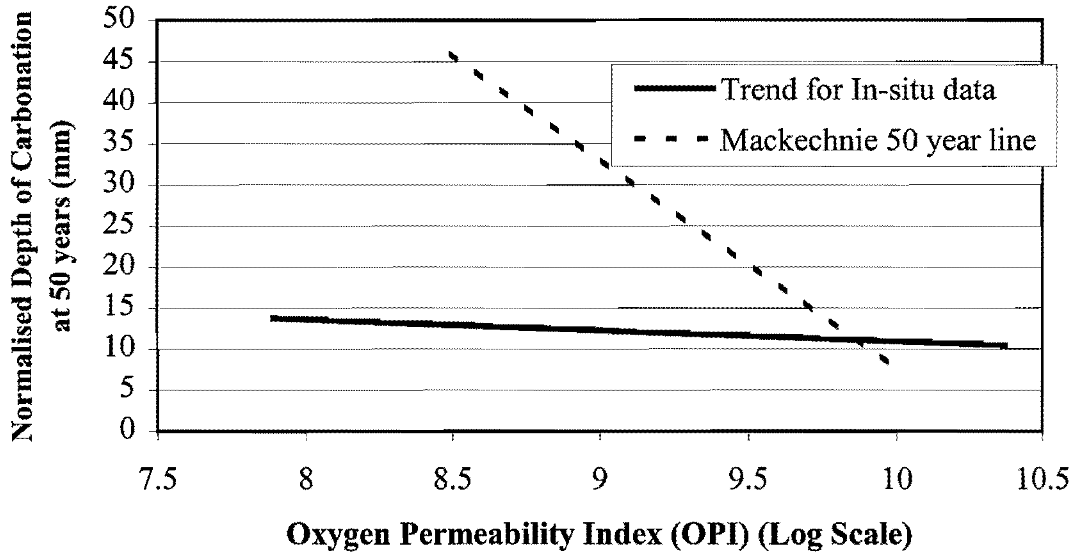


Figure 6.12: Predictions for carbonation at 50 years using OPI from Mackechnie (1999) model and in-situ carbonation data

There is a substantial difference between the prediction model derived by Mackechnie and the measured mature OPI relationship especially for low grade (quality) concretes with low OPI values. The predicted carbonation depth at 50 years from the mature OPI (i.e. "old" concretes) is dramatically lower than that from Mackechnie (i.e. "modern" concretes). This may due to: a change in cement properties particularly the fineness and the tricalcium silicate content; different environment of exposure; and "self-sealing" of the concrete surface.

- Change in cement properties

As explained in 5.3.6, the cement fineness and the tricalcium silicate content have increased in modern cements due to the economic benefits such as early removal of formwork. The consequences of using modern cements are: a higher water/binder ratio can be used to achieve the same concrete strength compared with use of old cements; the development of early age strength (cement hydration) is faster, the gain in later age strength may be of a small degree; and to some extent the formation of micro-cracks due to higher thermal contraction and drying shrinkage owing to the increase in heat of hydration. These consequences eventually lead to a difference in pore structure development between concretes produced by modern and old cements. OPI depends primarily on the pore structure, therefore, cement characteristics have an influence on OPI.

- Different environments of exposure

The prediction model obtained by Mackechnie (1999) was based on one environmental condition only whilst the trend line for the in-situ data includes different local environmental conditions which can have some effects on carbonation (see section 5.7 for more detail).

- Self-sealing of concrete surface

The possibility of the sealing of in-situ concrete surface pores by, e.g. dust, oily residues, pollutants, etc. in the congested urban environment may hinder the passage of carbon dioxide.

Changes in cement properties and the associated adverse effects on the permeability of concrete raise two important points relating to carbonation prediction. The carbonation prediction models derived in Chapter 5 which were based on old cements might not be suitable for predicting carbonation of modern/future concrete structures using modern cements. As it appears that concretes made from old cements generally have a slower rate of carbonation, this can under-estimate the carbonation rate for concretes made from modern cements. In other words, the derivation of carbonation prediction models for future concrete structures should be based on modern in-situ data.

It is also not correct to assume that the same water/cement ratio for old cement and modern cement will have the same OPI at 28 days, since the rate of cement hydration will differ. This will be explained in the following section in a way that first assumes the same water/cement ratio for both old cement and modern cement will have the same 28 day OPI and then shows this assumption to be invalid.

(b) Estimated 28 Day OPI

Assuming the same water/binder ratio for both old and modern cements will have the same OPI value at 28 days, the "Estimated OPI at 28 Days" can be obtained from the OPI calculator in the Concur Spreadsheet (available at UCT Website, http://www.civil.uct.ac.za/research/materials/concur.xls). This estimated OPI has the following input variables: 100% PC binder, Crane type mix with 50 – 75 mm slump and good site curing practice (i.e. moist curing for 7 days). It should be noted that the water/cement ratio used in the Concur spreadsheet should be the same as the "inferred water/cement" ratio given in Table 6.3.

It was stated previously that the OPI values given by Concur Spreadsheet are based on modern cements (i.e. cement manufactured from the mid-1990s), and thus it is not suitable for estimating OPI for old cements (i.e. before 1980s) as shown by comparing the measured mature OPI with the estimated 28 day OPI as shown in Figure 6.13 below.

As there are no reliable records on the curing practice for the bridges, it may be useful to compare the measured mature OPI with the estimated OPI at 28 days for poor site curing practice (i.e. no moist or air curing) as well (see Figure 6.14). Both Figures 6.13 and 6.14 show that the majority of the estimated 28 day OPI values are higher than the measured mature OPI values, although the values are more comparable for poor site curing practice than that of good site curing practice. This is a possible indication that some of the bridges were not cured according to good site curing practice. However, the estimated 28 day OPI values for both good and poor site curing practice should be smaller than the measured mature OPI, as OPI should improve with time due to the ongoing cement hydration effects, deposition of contaminants on the surface and the refinement of pore structure due to the process of carbonation which densify the pore structure and hence reduce permeability with time. This is generally the case.

The explanation for the anomaly can possibly be attributed to the change in cement properties, besides the facts that the variability of environmental exposure, contamination (if any) and its associated effects and interaction of other deterioration mechanisms such as cracking. As stated previously, the in-situ carbonation data were derived from old cements whilst the OPI calculator in the Concur Spreadsheet is designed for modern cements. The different rate of cement hydration of the two cements results in different rate of development of pore structure, and this has had an impact on the OPI values. This argument is supported by comparison between the inferred compressive strengths at 28 days for the old cements (in-situ data) and from the modern cements (calculated by Concur Spreadsheet which uses modern C & CI data from their website, http://www.cnci.org.co.za) as shown in Figure 6.15.

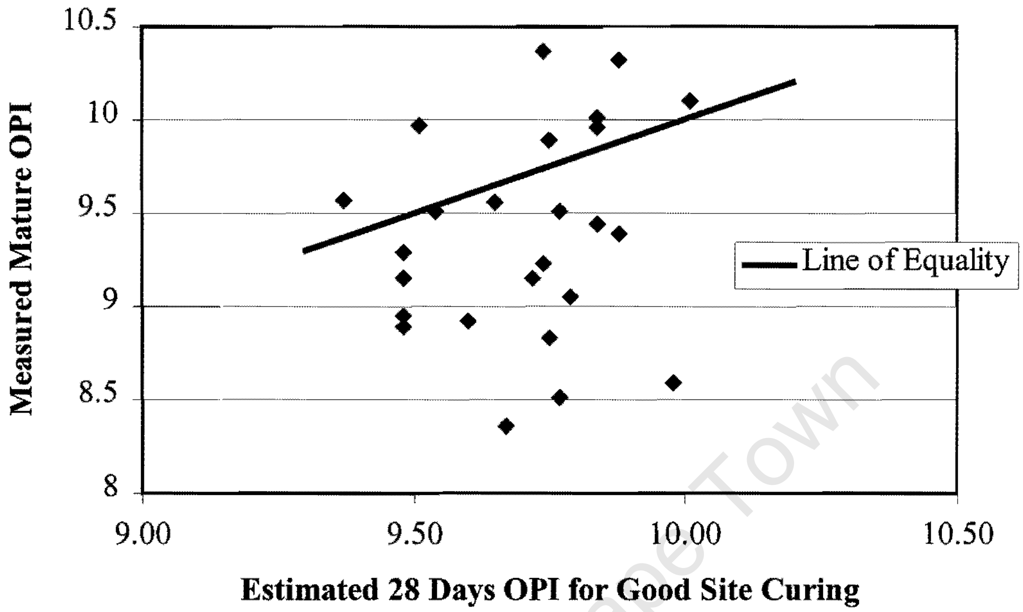


Figure 6.13: Comparison between measured mature and estimated 28 day OPI (with good site curing)

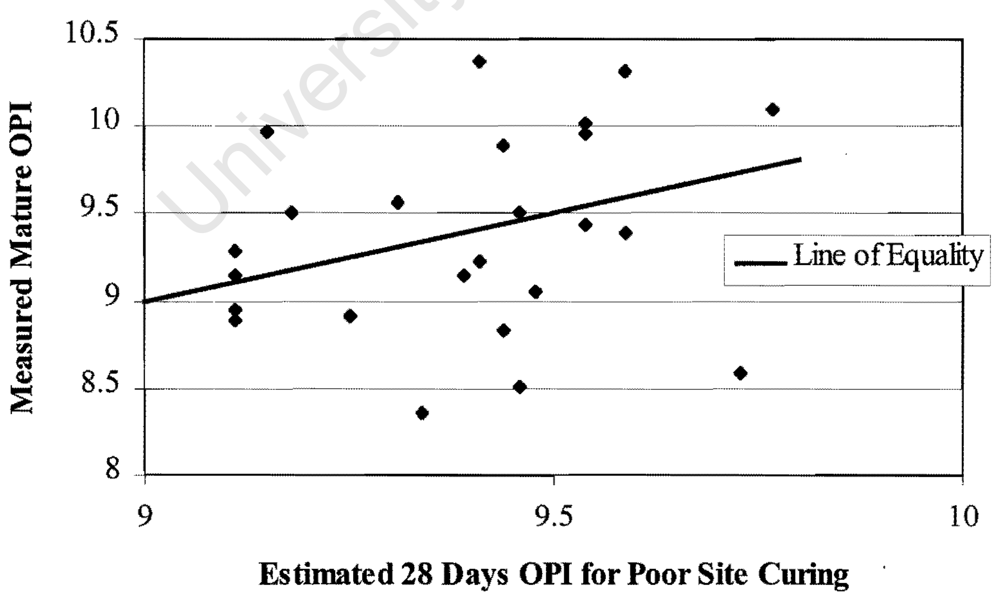


Figure 6.14: Comparison between measured mature and estimated 28 day OPI (with poor site curing)

Figure 6.15 shows that the compressive strength at 28 days produced by modern cements is higher than that of old cements by between 5 and 10 MPa at the same water/cement ratio. This difference in compressive strengths implies that the pore structures of concrete manufactured by the two cements at the same age (28 days) with the same water/cement ratio are different. Therefore, it is not appropriate to assume the OPI values (which are highly dependent on the pore structure of concrete) for old concretes based on the water/cement ratio of modern concretes.

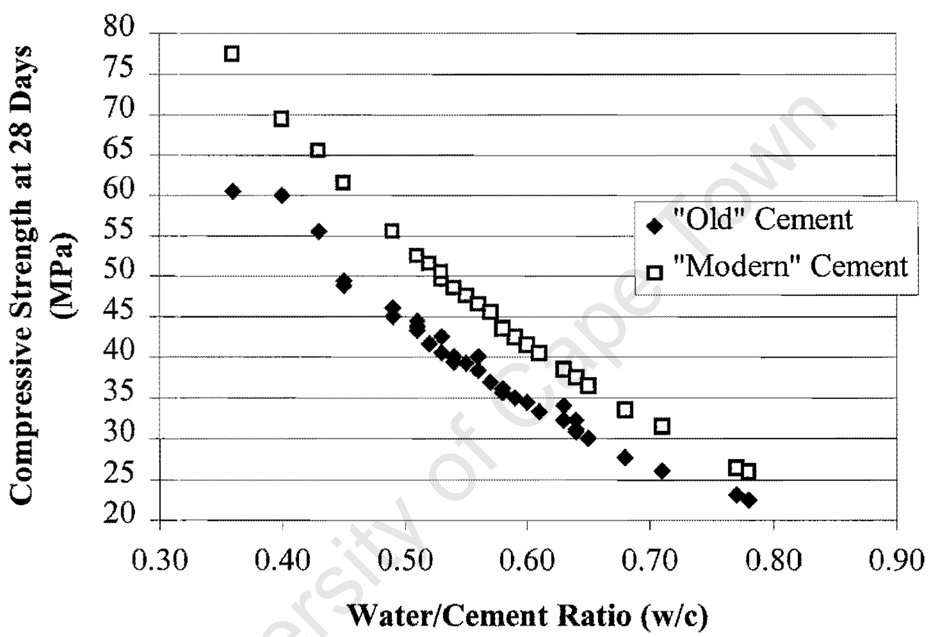


Figure 6.15: Compressive strength at 28 days produced by "old" and "modern" cements

Based on the above findings, the carbonation prediction models derived for old bridge structures (in Chapter 5) cannot be used for modern reinforced concrete structures. The carbonation prediction for modern and future structures should be derived from the field structures which are made from contemporary cements.

(c) Future Work

Since OPI has advantages for practical uses, and a better theoretical background in terms of characterising cover concrete permeability than compressive strength, the construction of the proposed chart given in Figure 6.8 is therefore useful for carbonation prediction. However, the above findings clearly show that using the carbonation data from the old structures is not correct to predict carbonation for modern/future structures. Therefore, it is necessary to obtain data from modern structures and follow the procedures given in Chapter 5 in order to derive carbonation prediction models for maintenance plan for existing modern structures.

It is also necessary to monitor in-situ carbonation in the long term for modern concretes to derive the correlation between depths of carbonation and OPI, as well as to check and/or improve Mackechnie's carbonation prediction model (based on OPI). After the correlation of carbonation depth and OPI is established, a carbonation predictions for any given time based on OPI can be obtained. The proposed carbonation prediction chart given in Figure 6.8 can then be constructed.

6.8 CONCLUDING SUMMARY

Current durability specifications are not adequate to specify for durable reinforced concrete structures. This is because the durability of concrete depends mainly on the transport mechanism of harmful species through the pores of concrete. Without a proper measure of the ingress of such species through the pore structure of concrete, durability cannot be assured.

Oxygen Permeability Index (OPI) measures fluids include both liquid and gas permeation through concrete under an externally applied pressure. As supported by short-term research work, OPI can predict carbonation depth because the OPI test can characterise gaseous penetrability through concrete. Therefore, OPI can also be thought of as a more suitable parameter in materials selection, specifying or designing for the durability of reinforced concrete structures against carbonation-induced corrosion.

The OPI test is easy, economical and only require a relatively short time to conduct. This brings advantages for use in practice such as site concrete quality control on curing and compaction.

An attempt to correlate carbonation depth of mature bridge structures in the Cape Peninsula locality with OPI has not been successful. This is attributed mainly to the change in cement properties. "Old" and "modern" cements have different fineness and (presumably) tricalcium silicate content thus the corresponding concrete would have different rates and development of pore structures. This also raises an important point that the carbonation prediction models based on old concrete structures are not suitable to predict carbonation for modern and future structures as the carbonation rate for these structures differ substantially. Therefore, carbonation data from modern structures should be sought and used to derive the carbonation prediction model for modern structures.

CHAPTER 7
GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 GENERAL DISCUSSION

The rates of carbonation of structural concrete in three South African localities were studied through the analysis of carbonation data obtained from in-service bridges. In-situ carbonation data were regarded as more valuable information than laboratory data from accelerated tests under controlled environments, because in-situ data derives from samples representative of local materials as well as exposed to "real" environments for a long period of time. Thus, they can better reflect the influences of materials and environment on rate of carbonation.

In order to understand the rate of carbonation and hence to avoid carbonation induced corrosion, the derivation of carbonation prediction models is necessary. The prediction model is in the form of a power model (i.e. $d_c = kt^n$). According to Fick's first law of diffusion, a square root of the time relationship results under stable and uniform conditions (i.e. the power series constant n is equal to 0.5). However, this square root relationship may not be suitable for concrete which is subject to wetting and drying cycles.

The in-situ data were grouped for similar properties in terms of exposure conditions and concrete strength grade prior to statistical analysis in order to determine the values for both k and n under the material and environmental effects for each locality. However, the data within each group were limited in both age and number, and also showed a very high variability. The high variability was presumed to result from the fact that the samples were extracted from different bridges subjected to batch and construction variability, as well as exposed to different exposure and service conditions. Thus, the derivation of prediction models based entirely on statistical analysis is difficult, as many combinations of k and n values can fit the data equally well. The derivation therefore requires the integration of the scientific principles, together with an understanding of the process of carbonation and the climatic conditions of the localities in conjunction with the statistical methods.

The rate of carbonation is controlled by the rate of carbon dioxide diffusion which is governed by the permeability and moisture conditions of the concrete. The ease of carbon dioxide diffusion into concrete depends on the degree of interconnectedness of the pores, which is reflected in a measure of permeability. The permeability of concrete is not constant with time and depth as carbonation progresses, because the formation and deposition of calcium carbonate in the pores can densify the pore system and hence reduce the permeability of concrete. On the other hand, diffusion of carbon dioxide also depends on the moisture condition of concrete pores which is influenced by climatic conditions. These two facts are very important considerations when deriving carbonation prediction models.

For the Cape Peninsula and Durban localities, the moisture content of the near-surface concrete is relatively high especially in the high rainfall season. Thus the rate of diffusion of carbon dioxide is slow, and so is the rate of carbonation. Consequently, the n values for the prediction models for these two localities were selected to be 0.4 in order to address the issues of reduction in permeability as carbonation progresses and high near-surface moisture content. On the other hand, the n value of 0.5 is selected for Johannesburg locality, as the relatively dry environment (within the optimum relative humidity range for carbonation) allows rapid carbonation throughout the year, and thus a more conservative value is chosen.

As the Johannesburg locality is relatively dry, the carbonation rate in this locality is the highest. Apart from relative humidity, temperature and rainfall pattern should also be taken into consideration in assessing the rate of carbonation. Although the annual average relative humidities for the Cape Peninsula and Durban localities are very similar, Durban locality has a higher rate of carbonation. This is mainly because the latter has a higher temperature as well as relatively short duration rainfall.

The rate of carbonation in Johannesburg locality is high but the likelihood of corrosion of steel reinforcement however is low. This is because its dry environment does not provide sufficient moisture to sustain corrosion. However, caution should be exercised as carbonation-induced corrosion can occur in members with low cover which are exposed to direct rain, or structures which are kept more damp due to poor drainage (e.g. leaking bridge joints).

Sufficient concrete cover should be ensured for structures in Cape Peninsula and Durban localities, as carbonation-induced corrosion is likely to occur due to the fact that carbonation occurs during the low rainfall season while corrosion takes place in the high rainfall season.

A difference in carbonation rates for the same concrete grades and exposure conditions was found in Durban locality, depending on the age of the bridges. Older concretes have slower carbonation rates than the modern concretes. This is possibly because of the change in cement properties with time. Economic necessities favour fast track construction which is a strong incentive to increase the rate of early strength gain of cement. The adverse effects are increased thermal effects (heat of hydration) and drying shrinkage resulting in the formation of micro-cracks which can speed up the transport of carbon dioxide (and other aggressive agents) through the concrete and hence jeopardise the concrete durability. This indicates that the change in cement characteristics may bring short term economic benefits but may imply a high cost of repair in the long run once the durability problem (such as cracking and spalling of concrete) is manifested. Furthermore, the difference in carbonation rates between older and modern concretes indicates that it is not possible to use models derived for older structures to predict carbonation rates of modern structures.

7.2 CONCLUSIONS OF THIS THESIS

The main aim for this thesis was to investigate the rate of carbonation in bridge structures in three South African localities (i.e. Cape Peninsula, Durban – KwaZulu Natal South Coast and Johannesburg area). Materials, environmental and construction factors that can affect the rate of carbonation of concrete were considered; and based on these factors, the obtained field carbonation data from in-service bridge structures were grouped prior to statistical analysis. The outcome from the statistical analysis was a series of carbonation prediction models. These models reflected the climatic conditions of the localities, as well as understanding of the process of carbonation. Through the derivation of carbonation prediction models for these localities, several conclusions can be drawn.

- **Risk of Carbonation-Induced Corrosion in the Localities**

According to the climatic conditions, the bridge structures in the Cape Peninsula and Durban localities have a greater risk of carbonation-induced corrosion than in the Johannesburg locality. In the former two localities, the low rainfall season promotes carbonation of concrete, whilst the high rainfall season sustains the corrosion of the embedded reinforcement. On the other hand, the dry environment throughout the year in the Johannesburg locality can produce rapid carbonation but vigorous corrosion of reinforcement is not very likely.

- **Derivation of Carbonation Prediction Model**

In order to derive a carbonation prediction model, both early and later age carbonation data should be obtained. This is because the rate of carbonation varies between early age and later age. Carbonation occurs more rapidly in the early age than in the later age. Therefore, the absence of either early or later age data will cause the prediction model to either underestimate the carbonation rate in the early ages, or overestimate the carbonation depth at later ages.

- **The Power Series Constant, n-Value**

The n values for Cape Peninsula and Durban localities were selected to be 0.4 instead of the theoretical value of 0.5, for ideal diffusion conditions. The high relative humidity in these localities does not favour the rapid ingress of carbon dioxide into concrete. However, relative humidity within the optimum relative humidity range for rapid carbonation throughout the year in the Johannesburg locality, leads to a higher (more conservative) n-value of 0.5 being selected.

- **Rate of Carbonation in the Localities**

The dry environment in Johannesburg locality exhibits the highest rate of carbonation. Durban locality has a higher rate of carbonation than the Cape Peninsula locality on the grounds that the former has a relatively short rainfall duration, as well as a higher temperature throughout the year.

- **Exposed and Sheltered Elements**

The rates of carbonation for the exposed and sheltered elements were compared separately in Durban and Johannesburg localities. It was shown that exposed and sheltered elements have similar rates of carbonation. This is because of the climatic conditions of these two localities. The short duration of rainfall and the high relative humidity in Durban locality yields only small differences in the near-surface moisture content between exposed and sheltered elements. On the other hand, the short rainfall duration and low relative humidity in Johannesburg locality render the near-surface moisture content for the exposed elements to be similar to that of the sheltered elements shortly after rain. As the moisture content of exposed and sheltered elements is similar, so is the rate of carbonation.

- **Variability of Field Carbonation Data**

A high variability was shown by the data, even though they were grouped in the same exposure conditions and similar concrete strength grade. This high variability is attributed to the fact that the field carbonation data were measured from in-situ bridge structures. Batch variability; different degrees and durations of site compaction and curing; the climatic conditions for the bridge structures in their early age; the variations in temperature and relative humidity caused by different orientations of the elements; the influences of cracks, moisture content (arising from joint leakage), and material inhomogeneity; and the interaction of these factors can lead to variability in the rate of carbonation for concretes with similar concrete strength grade.

- **Application of the Derived Carbonation Prediction Models**

The estimated 28 day compressive strengths for concretes produced by "old" cements and the "modern" cements at the same water/cement ratios are not the same. This suggests that the rates of pore structure development, gain in compressive strength and carbonation are not the same. Therefore, the carbonation prediction models derived in this thesis can only be applied to predict the depth of carbonation for the structures which were constructed in the same period as the bridge structures from which the carbonation data were measured. In other words, the carbonation prediction models derived in this thesis can be viewed as a means to prepare a maintenance plan, particularly to inform owners to source repair funding in advance.

- **Carbonation Predictions for Modern and Future Structures**

Due to the different rates of carbonation for old and modern structures, carbonation predictions for modern and future structures should be based on the corresponding structures which are constructed in the same period. In essence, the differences between old, modern and future structures can be distinguished mainly by the cement properties. As long as the structures are constructed using the cements or binders with the same properties, they can be classified in one group.

7.3 RECOMMENDATIONS FOR FUTURE WORK

In order to have a better understanding of carbonation of concrete and the derivation of more accurate carbonation prediction models for reinforced concrete structures, future work is recommended as follows:

- **Collection of More Field Data**

The collection of more field data aids the improvement of the prediction models that were derived in this thesis. Through the incorporation of more field data, from different structures subject to different local environments, with the data presented in this thesis, the reliability and quality of the derived prediction models can be improved in the sense that the prediction models can cover a broader range of local environments within the locality.

- **Proper Documentation of New Field Data**

Proper documentation of field data is crucial as this helps to group the data. The information required includes: name, age, year of construction, type of element, orientation, compressive strength (water/cement ratio), exposure conditions, physical location of the structures, and existing conditions of the structures, from which the carbonation data is measured. This helps to understand and classify the data.

- **Further Division of the Data**

After the collection and documentation of new data, if sufficient, a further division of the data can improve the quality of the prediction models. For example, other concrete strength grade bands can be used; the effect of the orientation of the elements on the rate of carbonation can also be studied, so that the structures can be designed or maintained according to the rate of carbonation of the most critical orientation.

- **Carbonation Predictions Based on Oxygen Permeability Index (OPI)**

It is useful to do the Oxygen Permeability Index (OPI) test at an early age, say at 28 days, for newly constructed structures and then correlate the values with the carbonation depths measured at both early and later ages. This is because OPI reflects the rate of carbon dioxide ingress; it is relatively quick and easy to assess the quality of cover concrete where carbonation takes place; and research shows that OPI may have promise to help predict depth of carbonation. Thus, work on the verification of the existing carbonation prediction model based on OPI is necessary.

The study of carbonation of concrete and the derivation of carbonation prediction models require ongoing research, including: collecting new field data, documenting the new data according to the database presented, incorporating the new field data with the field data provided, following the statistical analytical method demonstrated, considering the climatic effects on the process of carbonation, and heeding the issues recommended in this thesis. In time, reliable and accurate carbonation prediction models for the Cape Peninsula, Durban and Johannesburg localities, and other localities can be derived.

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APPENDIX A

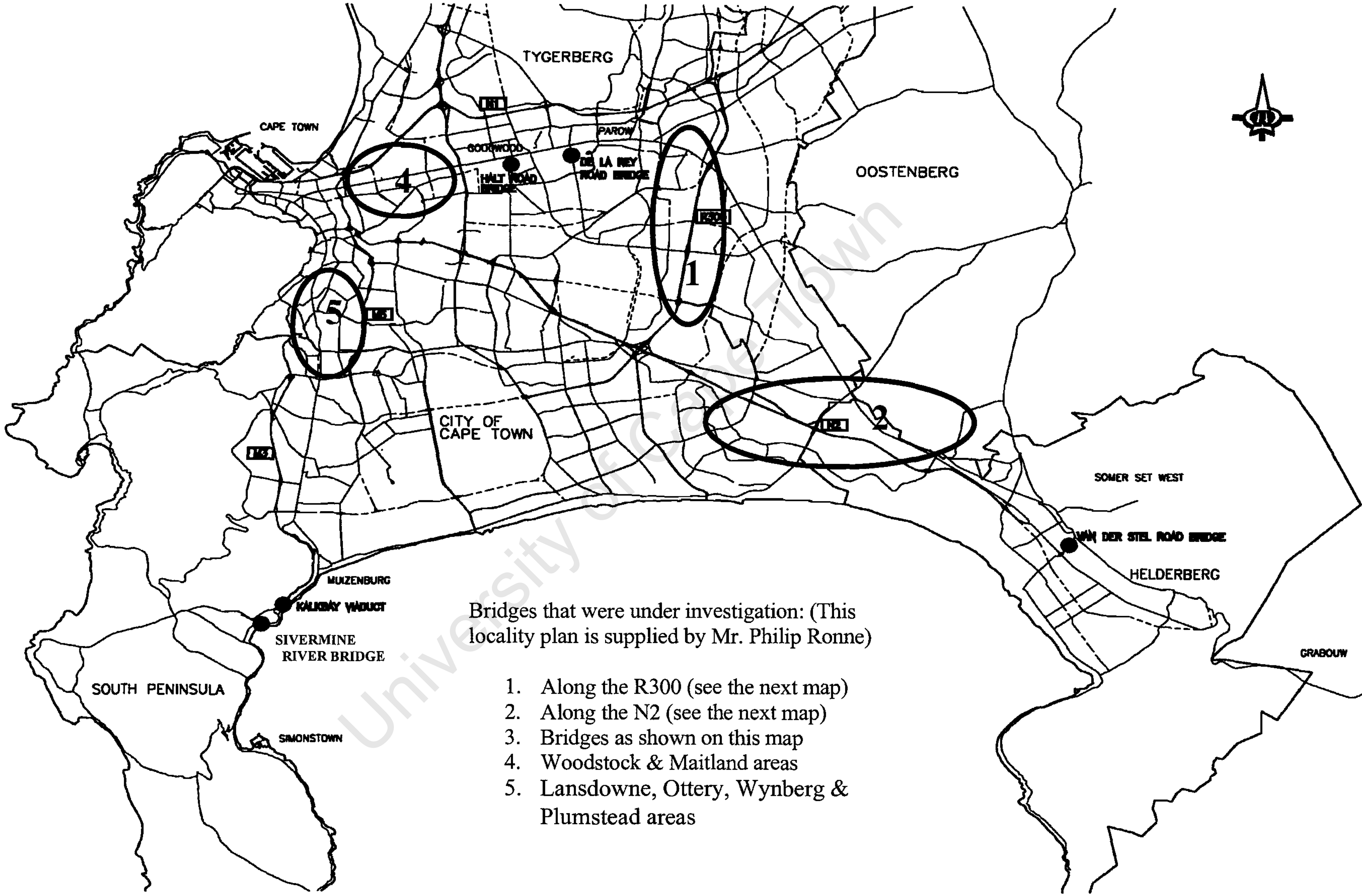
LOCALITY PLANS FOR THE BRIDGES IN THE THREE LOCALITIES

A1. Cape Peninsula Locality

A2. Durban Locality

A3. Johannesburg Locality

A1. CAPE PENINSULA LOCALITY

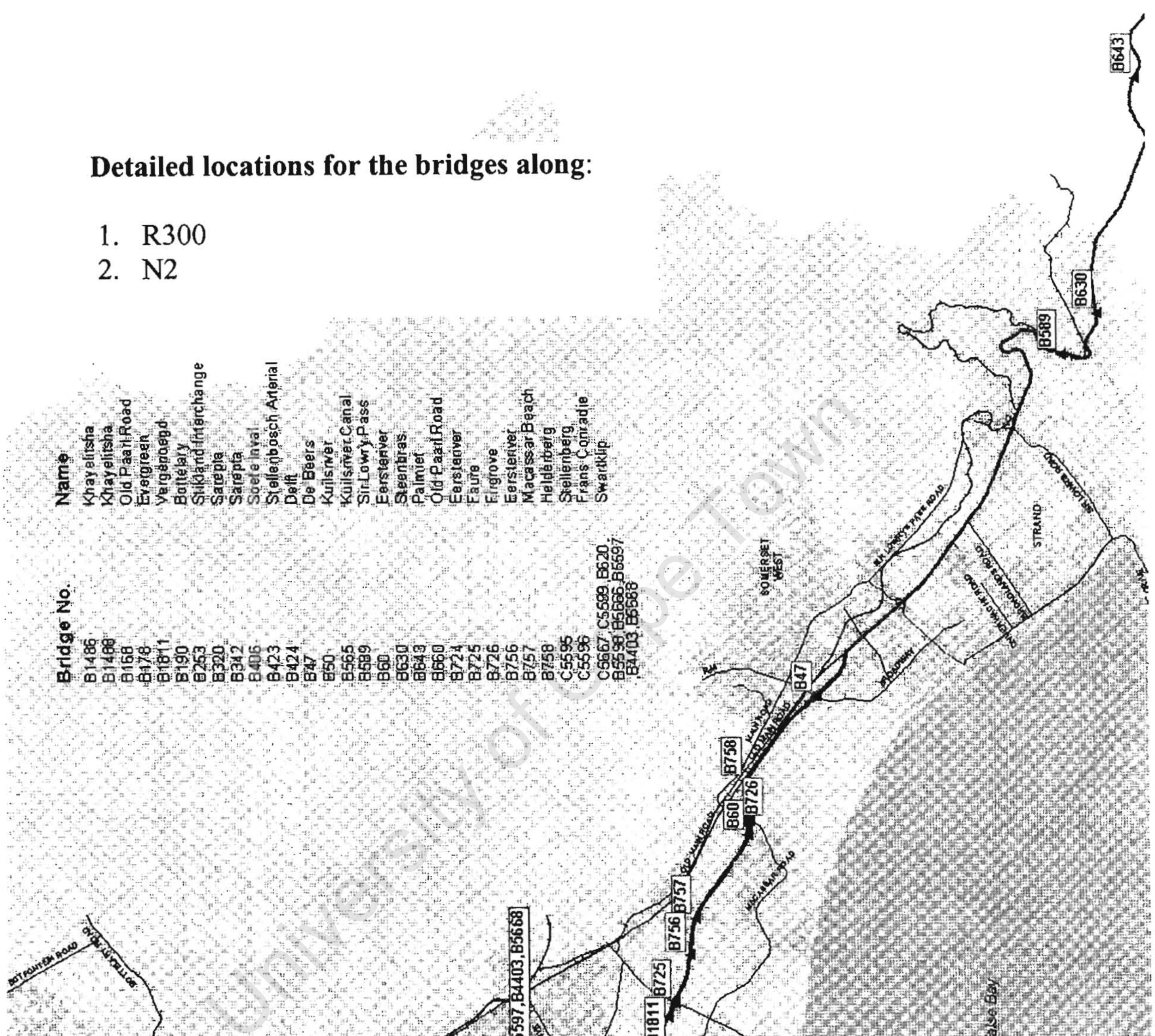


A1. CAPE PENINSULA LOCALITY (CON'T)

(This locality plan is supplied by Mr. Philip Ronne)

Detailed locations for the bridges along:

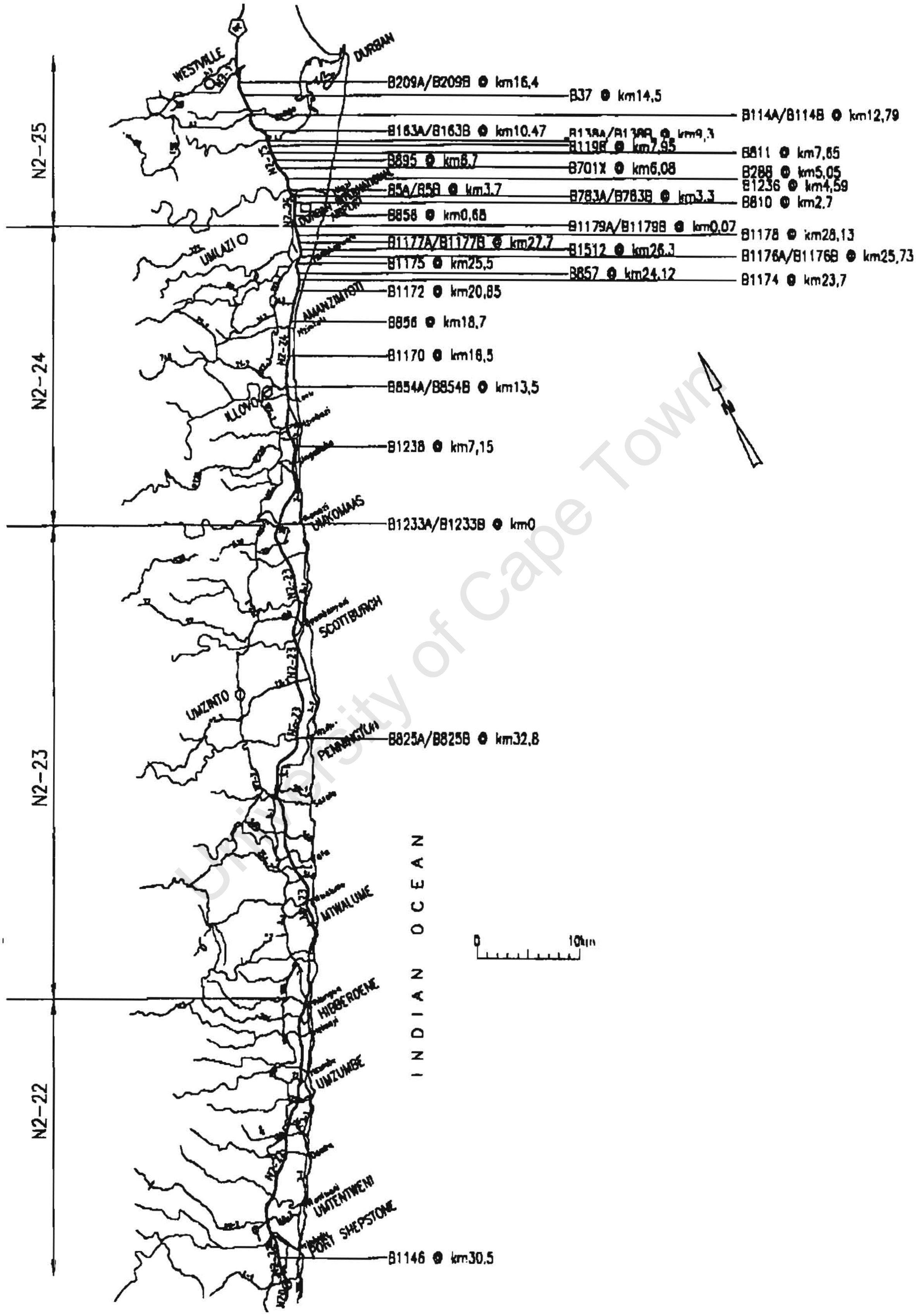
1. R300
2. N2



Bridge No.	Name
B1486	Khayelitsha
B1488	Khayelitsha
B168	Old Paarl Road
B178	Evergreen
B1811	Vergenoegd
B190	Bottelary
B253	Stikland Interchange
B320	Sarepta
B342	Sarepta
B406	Soete Inval
B423	Stellenbosch Arterial
B424	Delft
B47	De Beers
B50	Kuilsriver
B565	Kuilsriver Canal
B589	Sir Lowry Pass
B60	Eersteriver
B630	Steenbras
B643	Palmiet
B660	Old Paarl Road
B724	Eersteriver
B725	Faure
B726	Firgrove
B756	Eersteriver
B757	Macassar Beach
B758	Helderberg
C5595	Stellenberg
C5596	Frans Conradie
C5667, C5599, B620, B5598, B5666, B5597, B4403, B5668	Swartklip

A2. DURBAN LOCALITY

This locality plan is supplied by Mr Graham Moore.

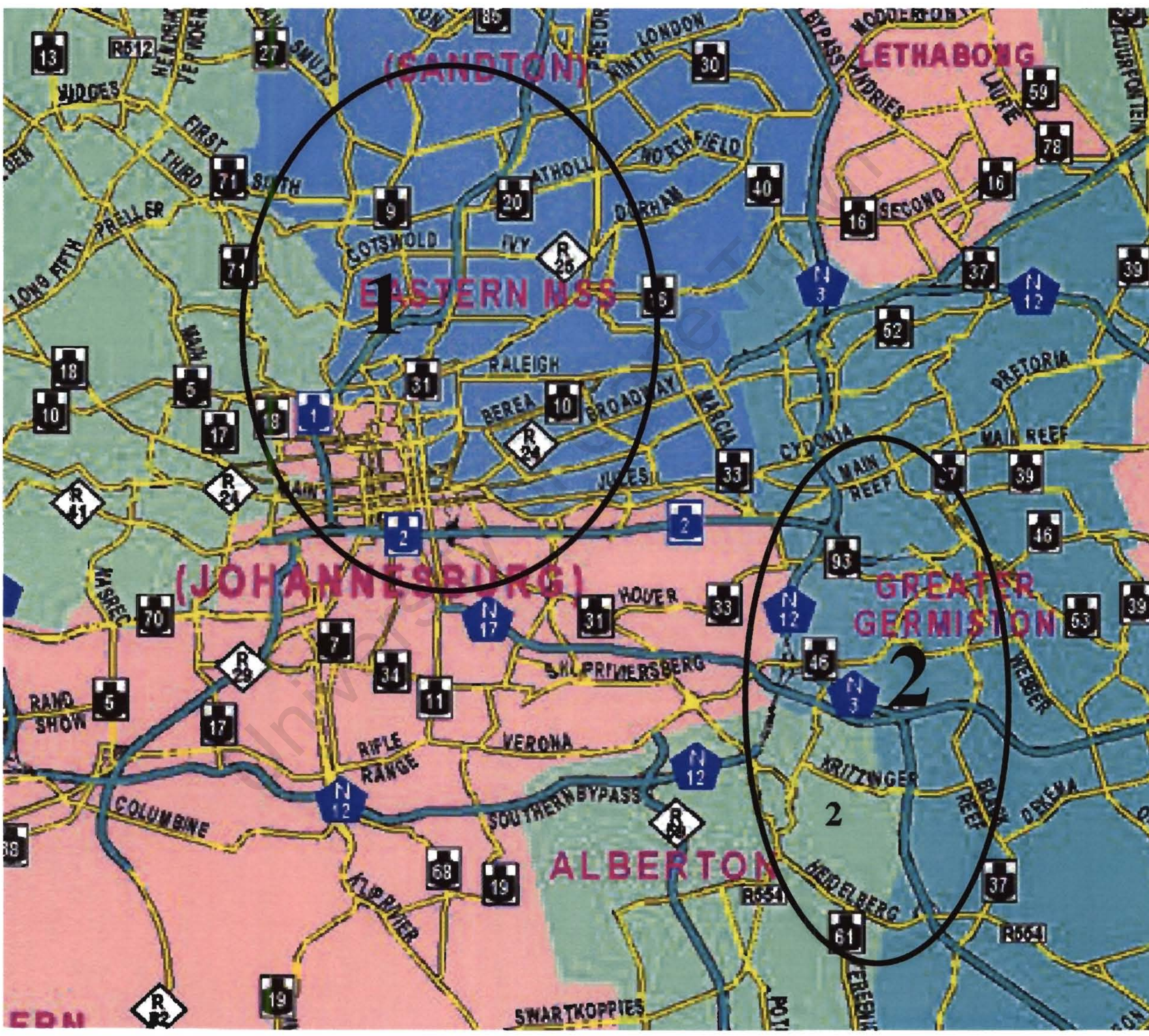


A3. JOHANNESBURG LOCALITY

This map is taken from: http://www.landsec.com/JHBmap.html

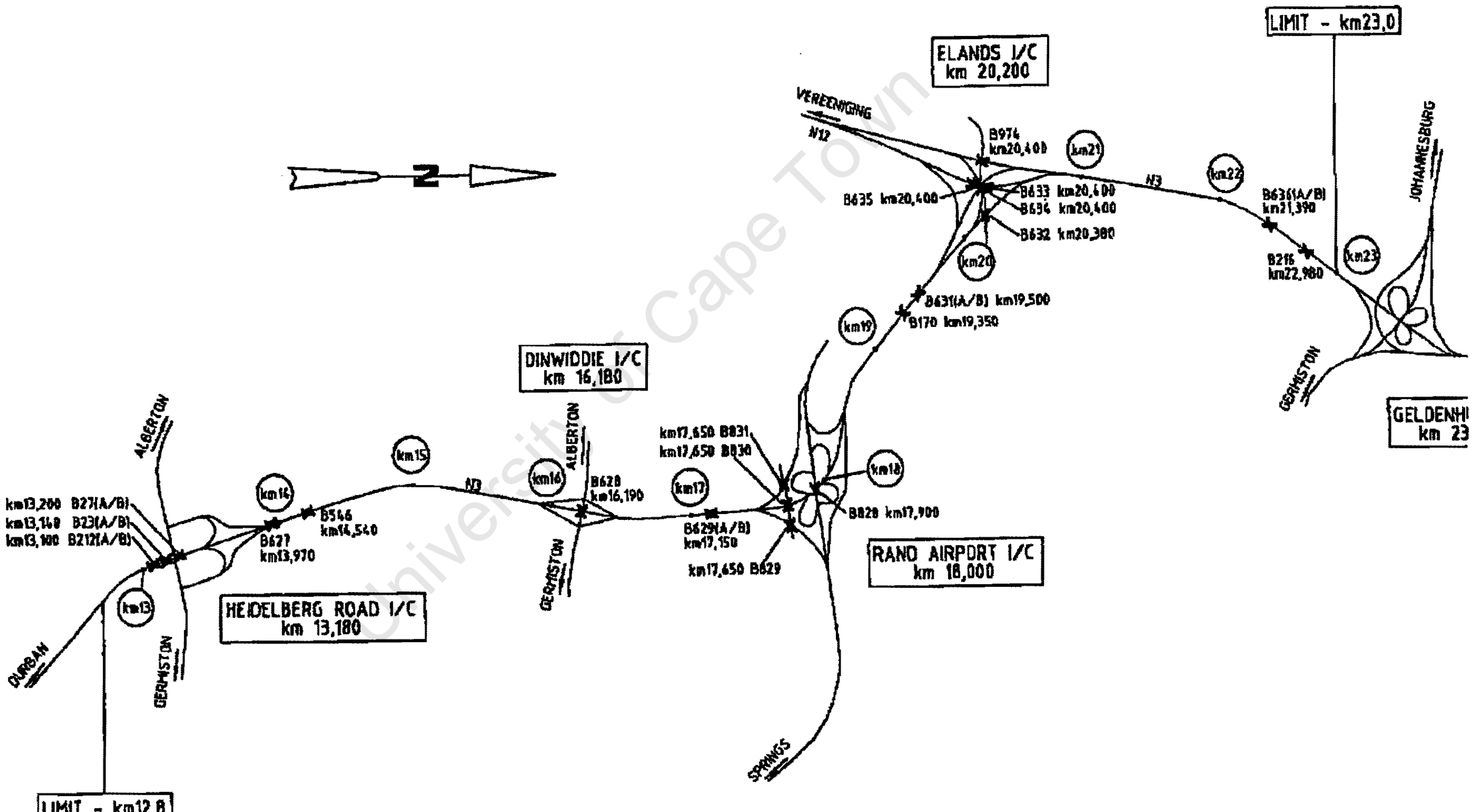
Bridges that were under investigation are (as shown in the map below):

1. The Johannesburg Motorway System, shown in the upper left hand portion
2. Along the N3 between Geldenhuis &Heidelberg Road Interchanges, in the lower right hand portion (see also the next map).



A3. JOHANNESBURG LOCALITY (CON'T)

The following plan shows details of the bridges between Heidelberg Road and Geldenhuis Interchanges along the N3 freeway (supplied by Mr. Graham Moore).



APPENDIX B

ANALYSIS OF CAPE PENINSULA DATA USING THE METHOD OF POWER REGRESSION

(Data were provided by Mr. Philip Ronne)

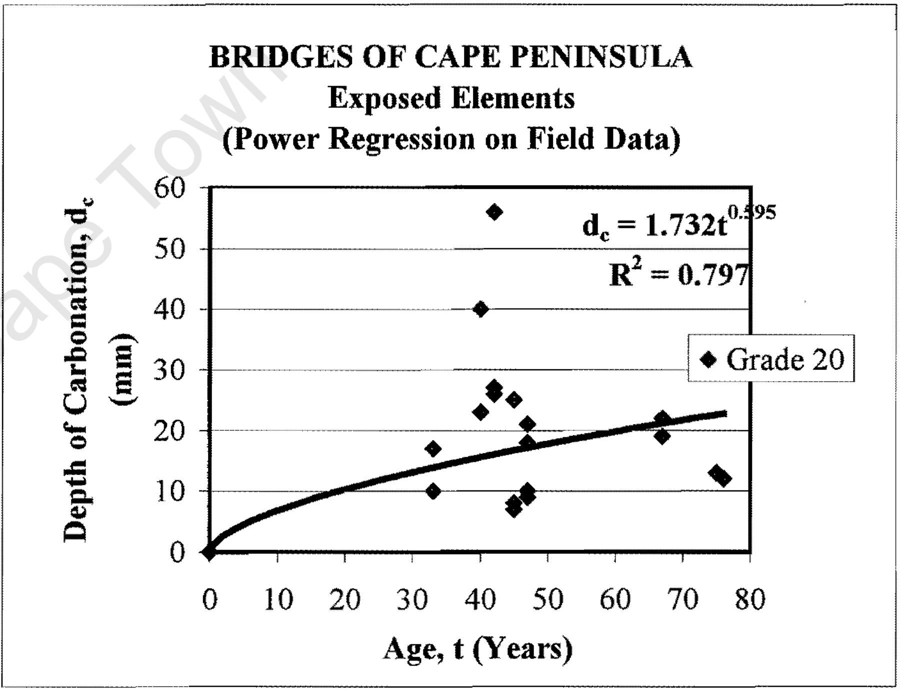
BRIDGES IN CAPE PENINSULA LOCALITY

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression Analysis on Field Data

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Measured d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	13.9	3.1
33	27.7	10	10	13.9	-3.9
40	30	40	40	15.6	24.4
40	30*	23	23	15.6	7.4
42	23.1	27	27	16.0	11.0
42	**30***	**56**	**56**	**16.0**	**40.0**
42	30	26	26	16.0	10.0
45	26.1	25	25	16.7	8.3
45	30*	8	8	16.7	-8.7
45	30*	7	7	16.7	-9.7
47	22.5	9	9	17.1	-8.1
47	30*	18	18	17.1	0.9
47	30*	10	10	17.1	-7.1
47	30*	21	21	17.1	3.9
67	30*	19	19	21.1	-2.1
67	30*	22	22	21.1	0.9
75	30*	13	13	22.6	-9.6
76	30*	12	12	22.8	-10.8
				Mean	**2.6**
				Std. Dev.	**12.8**
				+2x (Std. Dev.)	**25.6**
				-2x (Std. Dev.)	**-25.6**

Note: values in bold are outliers
* refers to assumed value



No. of Results: 18

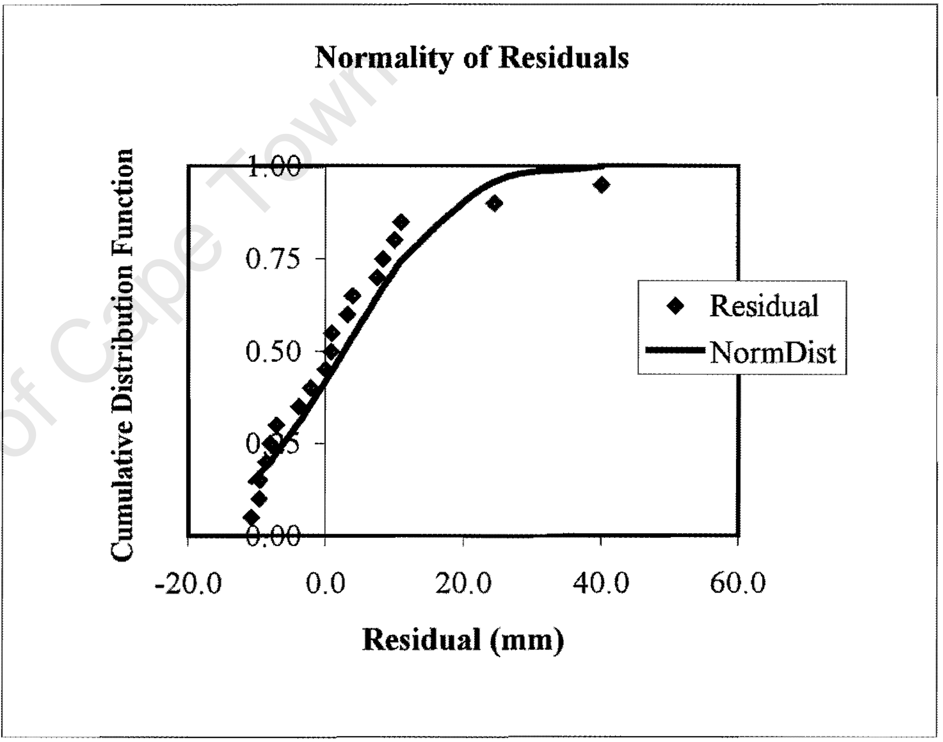
BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression on Field Data (Normality of Residuals)

Residual (mm)	Residual (sorted)	Rank (-)	Probabilit (P<d)	NormDist (-)
0.0	-10.8	1	0.05	0.15
3.1	-9.7	2	0.10	0.17
-3.9	-9.6	3	0.15	0.17
24.4	-8.7	4	0.20	0.19
7.4	-8.1	5	0.25	0.20
11.0	-7.1	6	0.30	0.22
40.0	-3.9	7	0.35	0.31
10.0	-2.1	8	0.40	0.35
8.3	0.0	9	0.45	0.42
-8.7	0.9	10	0.50	0.45
-9.7	0.9	11	0.55	0.45
-8.1	3.1	12	0.60	0.52
0.9	3.9	13	0.65	0.54
-7.1	7.4	14	0.70	0.65
3.9	8.3	15	0.75	0.67
-2.1	10.0	16	0.80	0.72
0.9	11.0	17	0.85	0.74
-9.6	24.4	18	0.90	0.96
-10.8	**40.0**	19	0.95	1.00

Note: The value in bold is the outlier. It is included here because the fitted model also contains this data point



BRIDGES IN CAPE PENINSULA LOCALITY

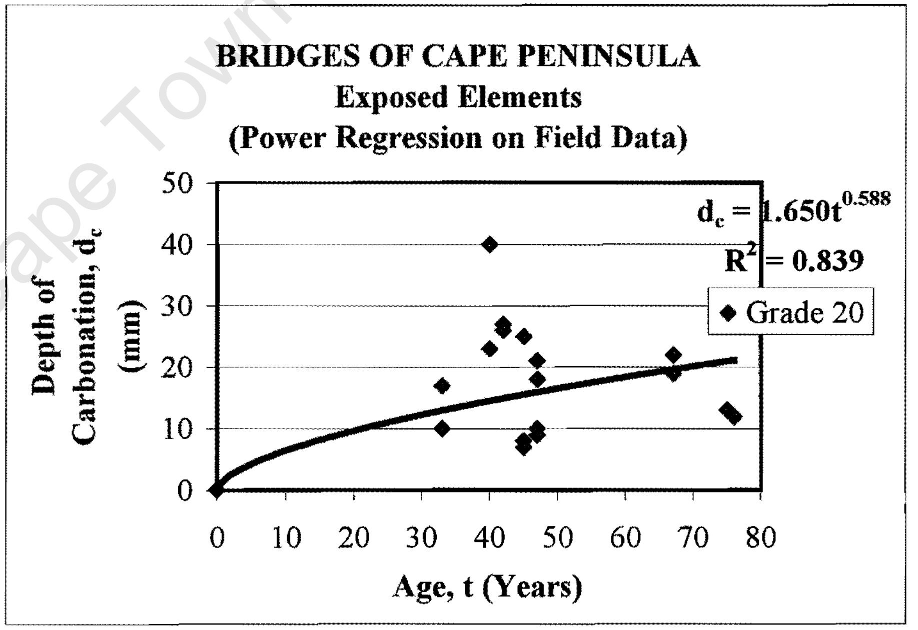
Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression Analysis on Field Data
(After the 1st Elimination of Gross Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Measured d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	12.9	4.1
33	27.7	10	10	12.9	-2.9
40	**30**	**40**	**40**	**14.4**	**25.6**
40	30*	23	23	14.4	8.6
42	23.1	27	27	14.9	12.1
42	30	26	26	14.9	11.1
45	26.1	25	25	15.5	9.5
45	30*	8	8	15.5	-7.5
45	30*	7	7	15.5	-8.5
47	22.5	9	9	15.9	-6.9
47	30*	18	18	15.9	2.1
47	30*	10	10	15.9	-5.9
47	30*	21	21	15.9	5.1
67	30*	19	19	19.6	-0.6
67	30*	22	22	19.6	2.4
75	30*	13	13	20.9	-7.9
76	30*	12	12	21.1	-9.1
				Mean	**1.8**
				Std. Dev.	**9.2**
				+2x (Std. Dev.)	**18.5**
				-2x (Std. Dev.)	**-18.5**

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17



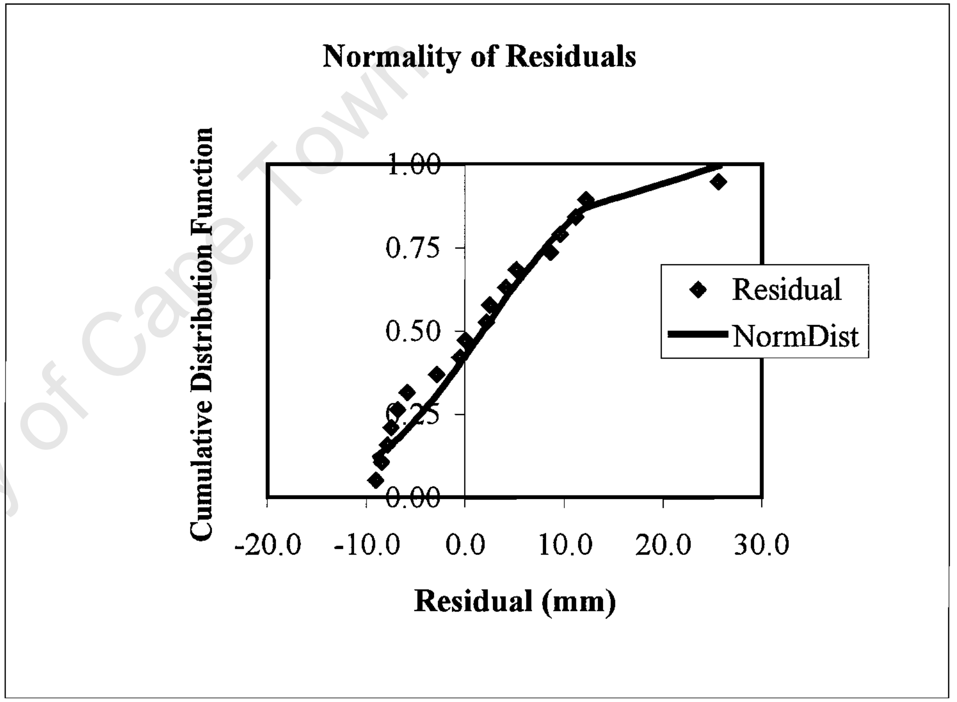
BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression on Field Data (Normality of Residuals)
(After the 1st Elimination of Gross Outliers)

Residual (mm)	Residual (sorted)	Rank (-)	Probabilit (P<d)	NormDist (-)
0.0	-9.1	1	0.05	0.12
4.1	-8.5	2	0.11	0.13
-2.9	-7.9	3	0.16	0.15
25.6	-7.5	4	0.21	0.16
8.6	-6.9	5	0.26	0.17
12.1	-5.9	6	0.32	0.20
11.1	-2.9	7	0.37	0.31
9.5	-0.6	8	0.42	0.40
-7.5	0.0	9	0.47	0.42
-8.5	2.1	10	0.53	0.52
-6.9	2.4	11	0.58	0.53
2.1	4.1	12	0.63	0.60
-5.9	5.1	13	0.68	0.64
5.1	8.6	14	0.74	0.77
-0.6	9.5	15	0.79	0.80
2.4	11.1	16	0.84	0.85
-7.9	12.1	17	0.89	0.87
-9.1	**25.6**	18	0.95	1.00

Note: The value in bold is the outlier. It is included here because the fitted model also contains this data point



BRIDGES IN CAPE PENINSULA LOCALITY

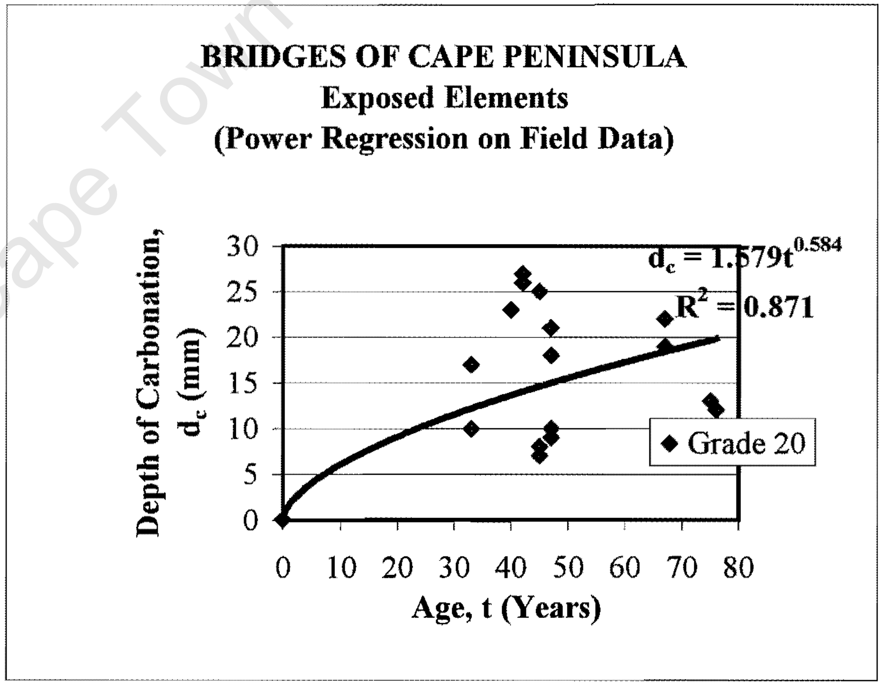
Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression Analysis on Field Data
(After the 2nd Elimination of Gross Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Measured d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
33	27.7*	17	17	12.2	4.8
33	27.7	10	10	12.2	-2.2
40	30*	23	23	13.6	9.4
42	23.1	27	27	14.0	13.0
42	30	26	26	14.0	12.0
45	26.1	25	25	14.6	10.4
45	30*	8	8	14.6	-6.6
45	30*	7	7	14.6	-7.6
47	22.5	9	9	15.0	-6.0
47	30*	18	18	15.0	3.0
47	30*	10	10	15.0	-5.0
47	30*	21	21	15.0	6.0
67	30*	19	19	18.4	0.6
67	30*	22	22	18.4	3.6
75	30*	13	13	19.7	-6.7
76	30*	12	12	19.8	-7.8
				Mean	**1.2**
				Std. Dev.	**7.2**
				+2x (Std. Dev.)	**14.5**
				-2x (Std. Dev.)	**-14.5**

* refers to assumed value

No. of Elements: 16

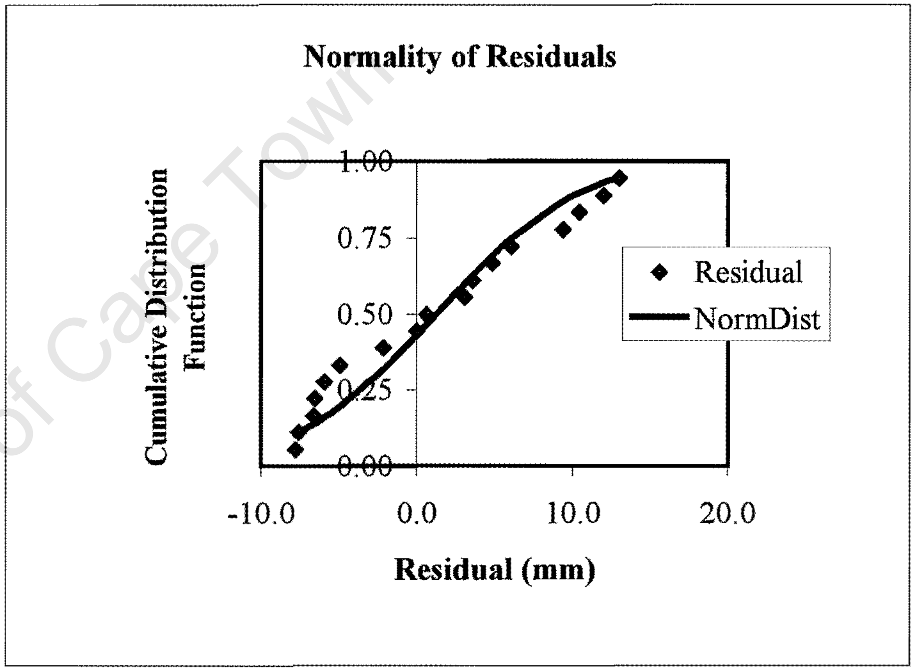


BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Power Regression on Field Data (Normality of Residuals)
(After the 2nd Elimination of Gross Outliers)

Residual (mm)	Residual (sorted)	Rank (-)	Probabilit (P<d)	NormDist (-)
0.0	-7.8	1	0.06	0.11
4.8	-7.6	2	0.11	0.11
-2.2	-6.7	3	0.17	0.14
9.4	-6.6	4	0.22	0.14
13.0	-6.0	5	0.28	0.16
12.0	-5.0	6	0.33	0.20
10.4	-2.2	7	0.39	0.32
-6.6	0.0	8	0.44	0.43
-7.6	0.6	9	0.50	0.46
-6.0	3.0	10	0.56	0.60
3.0	3.6	11	0.61	0.63
-5.0	4.8	12	0.67	0.69
6.0	6.0	13	0.72	0.75
0.6	9.4	14	0.78	0.87
3.6	10.4	15	0.83	0.90
-6.7	12.0	16	0.89	0.93
-7.8	13.0	17	0.94	0.95



BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 Days)

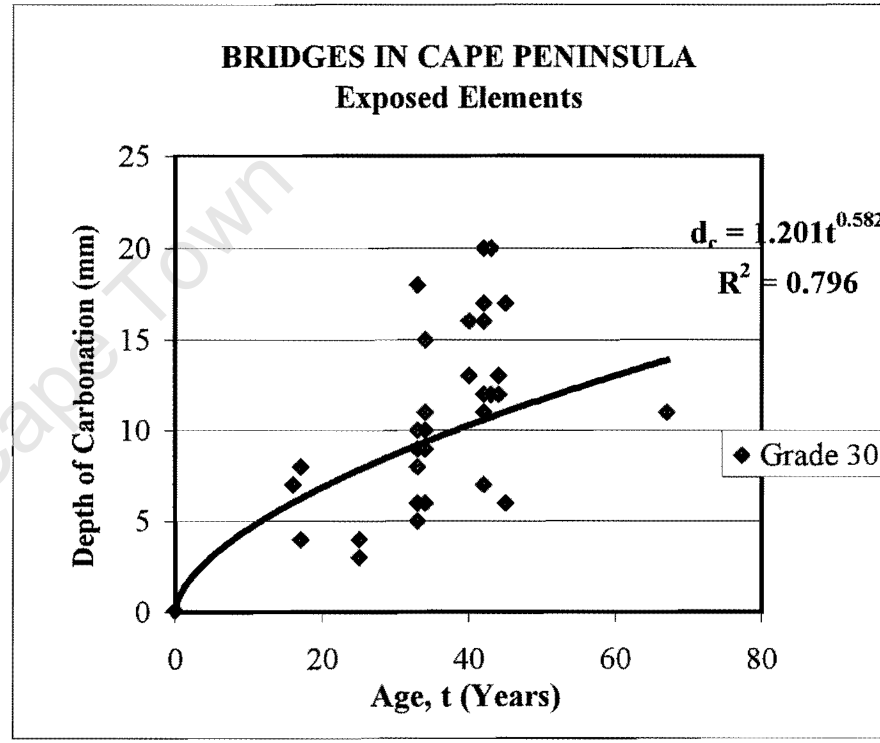
Method of Analysis: Power Regression on Field Data

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
33	39.4	8	8	9.2	-1.2
33	32.2	10	10	9.2	0.8
33	**32.2***	**18**	**18**	**9.2**	**8.8**
33	39.2*	5	5	9.2	-4.2
33	39.2	6	6	9.2	-3.2
33	39.2	9	9	9.2	-0.2
17	34*	4	4	6.2	-2.2
17	34	8	8	6.2	1.8
17	40*	4	4	6.2	-2.2
17	40*	4	4	6.2	-2.2
34	36.1	9	9	9.4	-0.4
34	36.1*	10	10	9.4	0.6
34	38.3	11	11	9.4	1.6
34	38.3*	15	15	9.4	5.6
34	35*	6	6	9.4	-3.4
40	40*	13	13	10.3	2.7
40	36.9	16	16	10.3	5.7
42	**34.4**	**20**	**20**	**10.6**	**9.4**
42	30.8	16	16	10.6	5.4
43	39.4	12	12	10.7	1.3
43	**39.4***	**20**	**20**	**10.7**	**9.3**
45	38.3	6	6	11.0	-5.0
45	38.3*	17	17	11.0	6.0
67	31.1	11	11	13.9	-2.9
42	33.3	12	12	10.6	1.4
42	33.3*	17	17	10.6	6.4
42	36.9	7	7	10.6	-3.6
42	36.9*	11	11	10.6	0.4
16	32.2	7	7	6.0	1.0
25	35.6*	4	4	7.8	-3.8
25	35.6	3	3	7.8	-4.8
44	30.8*	12	12	10.9	1.1
44	30.8	13	13	10.9	2.1
				Mean	**1.0**
				Std. Dev.	**4.1**
				+2x (Std. Dev.)	**8.2**
				-2x (Std. Dev.)	**-8.2**

Note: values in bold are outliers

* refers to assumed value

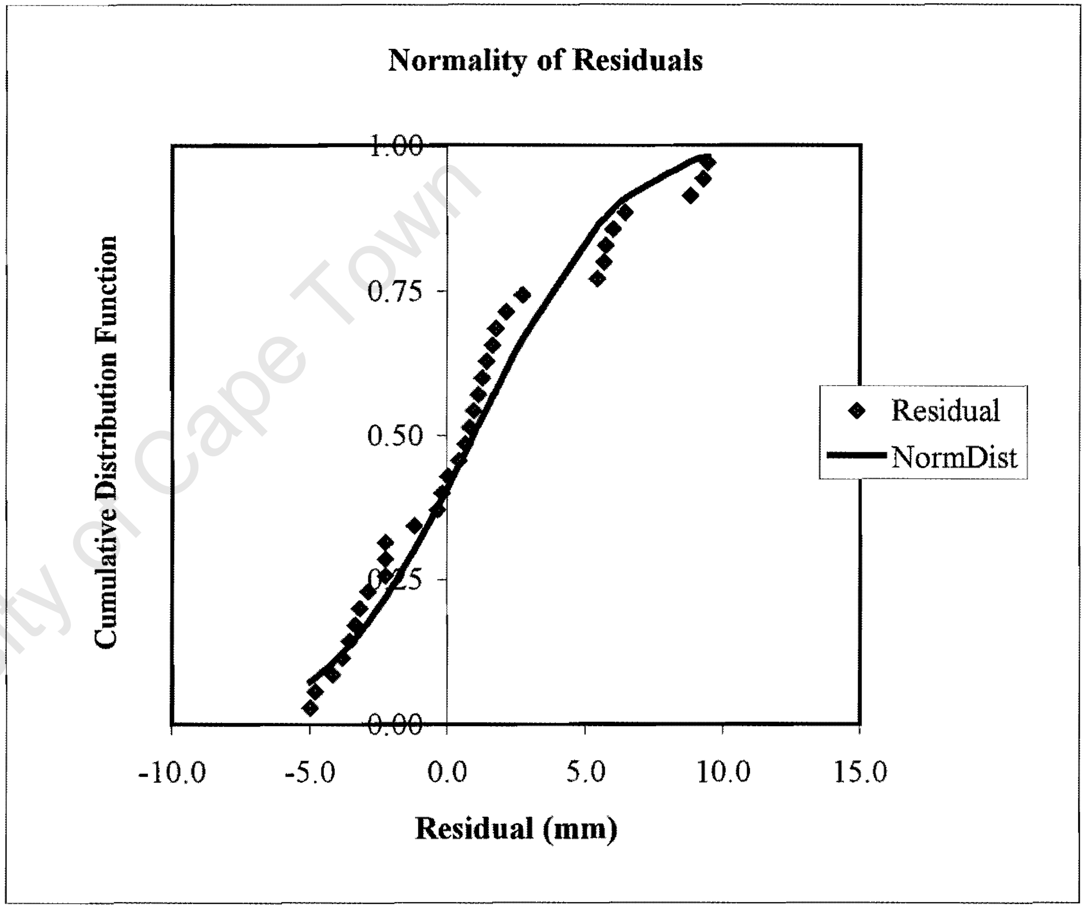
No. of Results: 33



Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)
Method of Analysis: Power Regression on Field Data (Normality of Residuals)

Residual (mm)	Residual (sorted)	Rank (-)	Probability (P<d)	NormDist (-)
0.0	-5.0	1	0.03	0.07
-1.2	-4.8	2	0.06	0.08
0.8	-4.2	3	0.09	0.11
8.8	-3.8	4	0.11	0.12
-4.2	-3.6	5	0.14	0.14
-3.2	-3.4	6	0.17	0.15
-0.2	-3.2	7	0.20	0.16
-2.2	-2.9	8	0.23	0.18
1.8	-2.2	9	0.26	0.22
-2.2	-2.2	10	0.29	0.22
-2.2	-2.2	11	0.31	0.22
-0.4	-1.2	12	0.34	0.30
0.6	-0.4	13	0.37	0.38
1.6	-0.2	14	0.40	0.39
5.6	0.0	15	0.43	0.41
-3.4	0.4	16	0.46	0.45
2.7	0.6	17	0.49	0.47
5.7	0.8	18	0.51	0.49
9.4	1.0	19	0.54	0.50
5.4	1.1	20	0.57	0.52
1.3	1.3	21	0.60	0.53
9.3	1.4	22	0.63	0.55
-5.0	1.6	23	0.66	0.57
6.0	1.8	24	0.69	0.58
-2.9	2.1	25	0.71	0.61
1.4	2.7	26	0.74	0.67
6.4	5.4	27	0.77	0.86
-3.6	5.6	28	0.80	0.87
0.4	5.7	29	0.83	0.88
1.0	6.0	30	0.86	0.89
-3.8	6.4	31	0.89	0.91
-4.8	**8.8**	32	0.91	0.97
1.1	**9.3**	33	0.94	0.98
2.1	**9.4**	34	0.97	0.98

Note: values in bold are gross outliers



BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 Days)

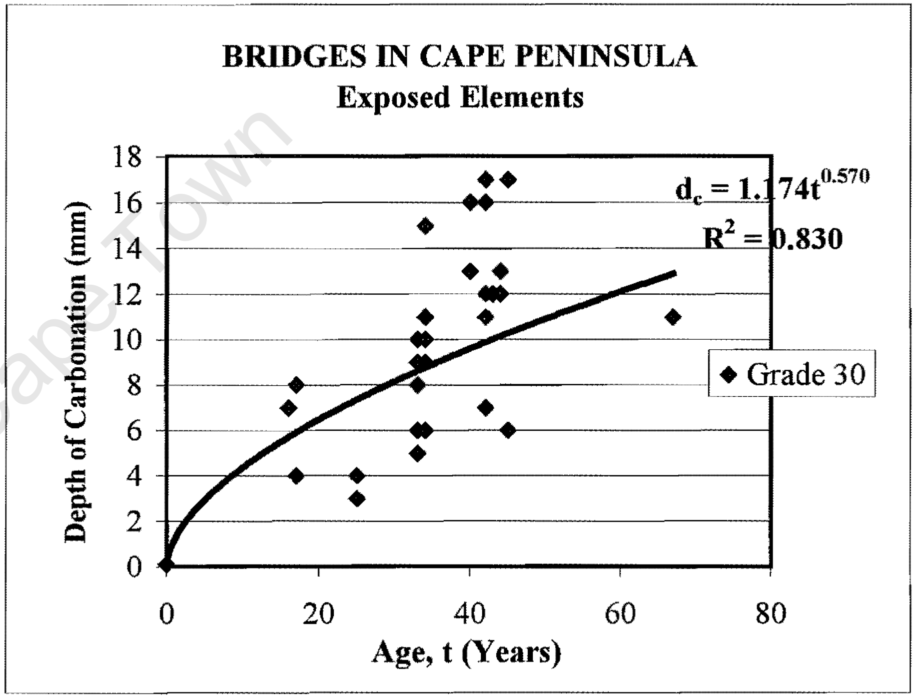
Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
33	39.4	8	8	8.6	-0.6
33	32.2	10	10	8.6	1.4
33	39.2*	5	5	8.6	-3.6
33	39.2	6	6	8.6	-2.6
33	39.2	9	9	8.6	0.4
17	34*	4	4	5.9	-1.9
17	34	8	8	5.9	2.1
17	40*	4	4	5.9	-1.9
17	40*	4	4	5.9	-1.9
34	36.1	9	9	8.8	0.2
34	36.1*	10	10	8.8	1.2
34	38.3	11	11	8.8	2.2
34	38.3*	15	15	8.8	6.2
34	35*	6	6	8.8	-2.8
40	40*	13	13	9.6	3.4
40	36.9	16	16	9.6	6.4
42	30.8	16	16	9.9	6.1
43	39.4	12	12	10.0	2.0
45	38.3	6	6	10.3	-4.3
45	38.3*	17	17	10.3	6.7
67	31.1	11	11	12.9	-1.9
42	33.3	12	12	9.9	2.1
42	33.3*	17	17	9.9	7.1
42	36.9	7	7	9.9	-2.9
42	36.9*	11	11	9.9	1.1
16	32.2	7	7	5.7	1.3
25	35.6*	4	4	7.4	-3.4
25	35.6	3	3	7.4	-4.4
44	30.8*	12	12	10.1	1.9
44	30.8	13	13	10.1	2.9
				Mean	**0.7**
				Std. Dev.	**3.4**
				+2x (Std. Dev.)	**6.8**
				-2x (Std. Dev.)	**-6.8**

Note: * refers to assumed value

No. of Results: 30

Method of Analysis: Power Regression on Field Data

(After the 1st Elimination of Gross Outliers)



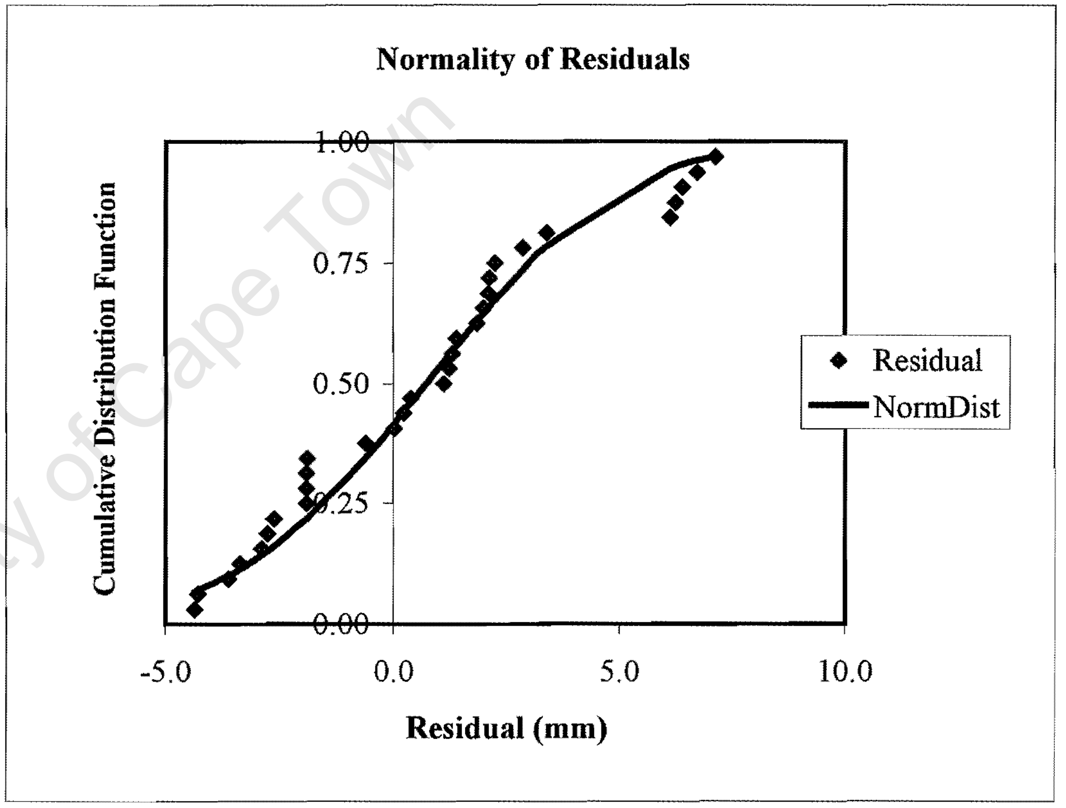
Note: Only one elimination of gross outliers is carried out in this special case because the continuous elimination would reject the whole population group of high carbonation depths

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)

Method of Analysis: Power Regression on Field Data (Normality of Residuals)
(After the 2nd Elimination of Gross Outliers)

Residual (mm)	Residual (sorted)	Rank (-)	Probability (P<d)	NormDist (-)
0.0	-4.4	1	0.03	0.07
-0.6	-4.3	2	0.06	0.07
1.4	**-3.6**	3	0.09	0.10
-3.6	-3.4	4	0.13	0.11
-2.6	-2.9	5	0.16	0.14
0.4	-2.8	6	0.19	0.15
-1.9	-2.6	7	0.22	0.16
2.1	-1.9	8	0.25	0.22
-1.9	-1.9	9	0.28	0.22
-1.9	-1.9	10	0.31	0.22
0.2	-1.9	11	0.34	0.22
1.2	-0.6	12	0.38	0.35
2.2	0.0	13	0.41	0.42
6.2	0.2	14	0.44	0.44
-2.8	0.4	15	0.47	0.46
3.4	1.1	16	0.50	0.55
6.4	1.2	17	0.53	0.56
6.1	1.3	18	0.56	0.57
2.0	1.4	19	0.59	0.58
-4.3	1.9	20	0.63	0.63
6.7	2.0	21	0.66	0.64
-1.9	2.1	22	0.69	0.66
2.1	2.1	23	0.72	0.66
7.1	2.2	24	0.75	0.67
-2.9	2.9	25	0.78	0.73
1.1	3.4	26	0.81	0.78
1.3	6.1	27	0.84	0.94
-3.4	6.2	28	0.88	0.95
-4.4	6.4	29	0.91	0.95
1.9	6.7	30	0.94	0.96
2.9	7.1	31	0.97	0.97

Note: values in bold are gross outliers



BRIDGES OF CAPE PENINSULA

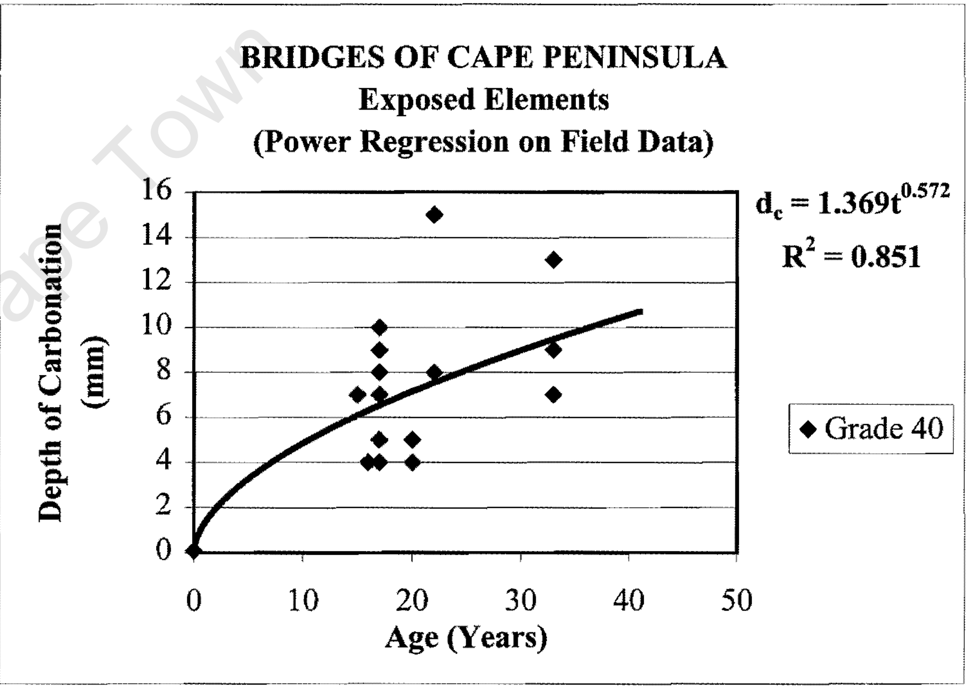
Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Power Regression Analysis on Field Data

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
15	49.4	7	7	6.4	0.6
15	49.4*	7	7	6.4	0.6
16	42.5	4	4	6.7	-2.7
17	46.38	8	8	6.9	1.1
17	46.38*	7	7	6.9	0.1
17	43.8*	5	5	6.9	-1.9
17	43.8	4	4	6.9	-2.9
17	43.3	9	9	6.9	2.1
17	43.3	10	10	6.9	3.1
20	44.4*	4	4	7.6	-3.6
20	44.4	5	5	7.6	-2.6
22	45*	8	8	8.0	0.0
22	45	8	8	8.0	0.0
22	41.6*	15	15	8.0	7.0
22	**41.6**	**18**	**18**	8.0	**10.0**
33	40.5	8	8	10.1	-2.1
33	40.5	9	9	10.1	-1.1
33	48.8	13	13	10.1	2.9
33	**48.8***	**19**	**19**	10.1	**8.9**
41	41.6	7	7	11.5	-4.5
				Mean	**0.7**
				Std. Dev.	**3.9**
				+2x (Std. Dev.)	**7.8**
				-2x (Std. Dev.)	**-7.8**

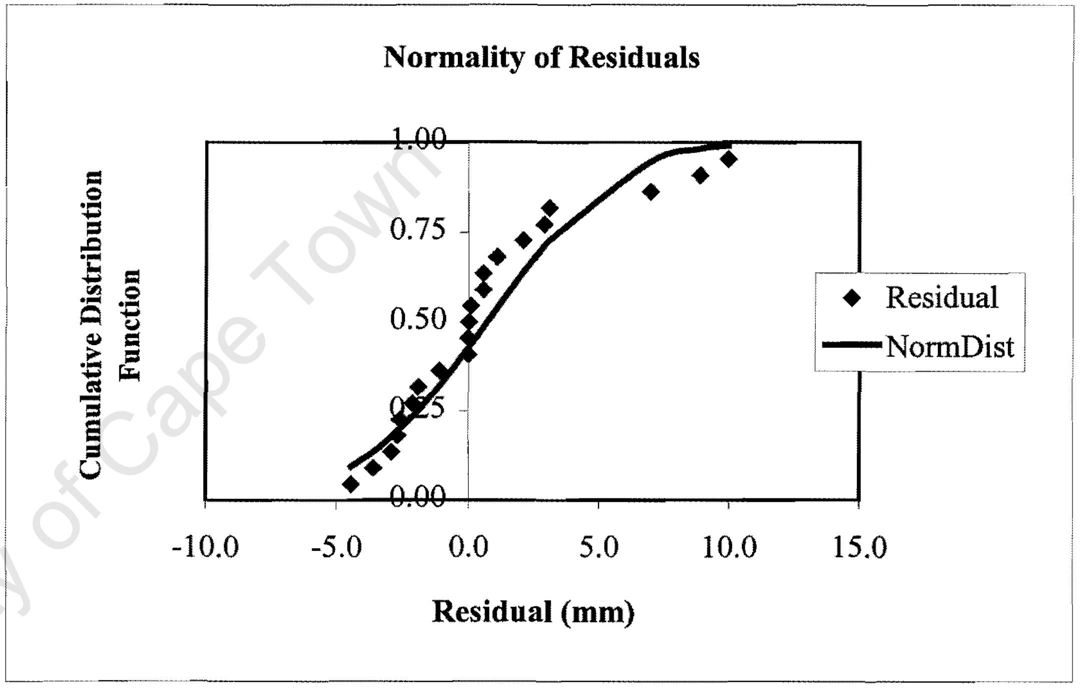
Note: values in bold are outliers
* refers to assumed value

No. of Results: 20



Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)
Method of Analysis: Power Regression on Field Data (Normality of Residuals)

Residual (mm)	Residual (sorted)	Rank (-)	Probability (P<d)	NormDist (-)
0.0	-4.5	1	0.05	0.09
0.6	-3.6	2	0.09	0.14
0.6	-2.9	3	0.14	0.18
-2.7	-2.7	4	0.18	0.19
1.1	-2.6	5	0.23	0.20
0.1	-2.1	6	0.27	0.24
-1.9	-1.9	7	0.32	0.25
-2.9	-1.1	8	0.36	0.32
2.1	0.0	9	0.41	0.43
3.1	0.0	10	0.45	0.43
-3.6	0.0	11	0.50	0.43
-2.6	0.1	12	0.55	0.44
0.0	0.6	13	0.59	0.49
0.0	0.6	14	0.64	0.49
7.0	1.1	15	0.68	0.54
10.0	2.1	16	0.73	0.64
-2.1	2.9	17	0.77	0.71
-1.1	3.1	18	0.82	0.73
2.9	7.0	19	0.86	0.95
8.9	**8.9**	20	0.91	0.98
-4.5	**10.0**	21	0.95	0.99



Note: values in bold are gross outliers

BRIDGES OF CAPE PENINSULA

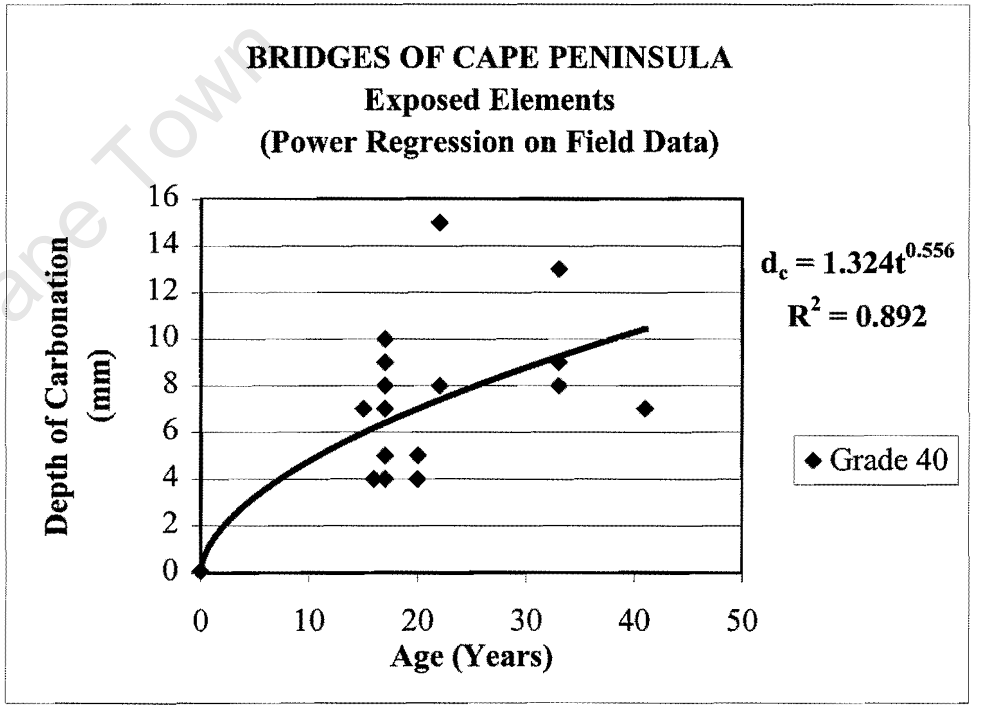
Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Power Regression Analysis on Field Data
(After 1st Elimination of Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.1	0.0
15	49.4	7	7	6.0	1.0
15	49.4*	7	7	6.0	1.0
16	42.5	4	4	6.2	-2.2
17	46.38	8	8	6.4	1.6
17	46.38*	7	7	6.4	0.6
17	43.8*	5	5	6.4	-1.4
17	43.8	4	4	6.4	-2.4
17	43.3	9	9	6.4	2.6
17	43.3	10	10	6.4	3.6
20	44.4*	4	4	7.0	-3.0
20	44.4	5	5	7.0	-2.0
22	45*	8	8	7.4	0.6
22	45	8	8	7.4	0.6
22	**41.6***	**15**	**15**	**7.4**	**7.6**
33	40.5	8	8	9.3	-1.3
33	40.5	9	9	9.3	-0.3
33	48.8	13	13	9.3	3.7
41	41.6	7	7	10.4	-3.4
				Mean	**0.4**
				Std. Dev.	**2.7**
				+2x (Std. Dev.)	**5.5**
				-2x (Std. Dev.)	**-5.5**

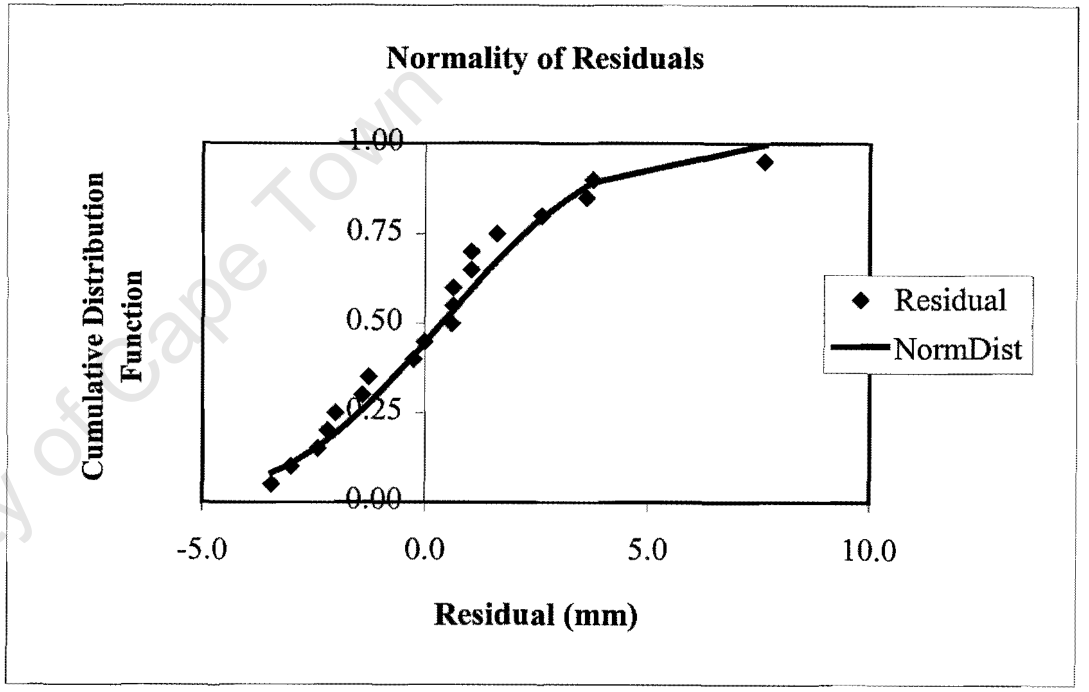
Note: values in bold are outliers
* refers to assumed value

No. of Results: 18



Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)
Method of Analysis: Power Regression on Field Data (Normality of Residuals)
(After the 1st Elimination of Gross Outliers)

Residual (mm)	Residual (sorted)	Rank (-)	Probability (P<d)	NormDist (-)
0.0	-3.4	1	0.05	0.08
1.0	-3.0	2	0.10	0.11
1.0	-2.4	3	0.15	0.15
-2.2	-2.2	4	0.20	0.17
1.6	-2.0	5	0.25	0.19
0.6	-1.4	6	0.30	0.26
-1.4	-1.3	7	0.35	0.28
-2.4	-0.3	8	0.40	0.41
2.6	0.0	9	0.45	0.44
3.6	0.6	10	0.50	0.53
-3.0	0.6	11	0.55	0.54
-2.0	0.6	12	0.60	0.54
0.6	1.0	13	0.65	0.60
0.6	1.0	14	0.70	0.60
7.6	1.6	15	0.75	0.67
-1.3	2.6	16	0.80	0.79
-0.3	3.6	17	0.85	0.88
3.7	3.7	18	0.90	0.89
-3.4	**7.6**	19	0.95	1.00



Note: values in bold are gross outliers

BRIDGES OF CAPE PENINSULA

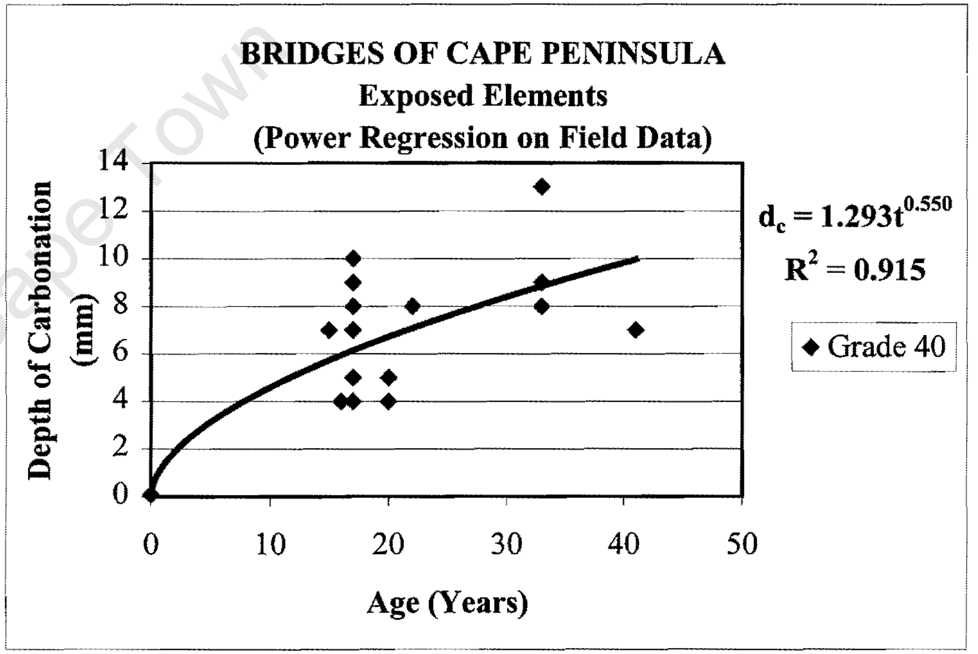
Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Power Regression Analysis on Field Data
(After 2nd Elimination of Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t)	Strength	d_c	Observed d_c	Predicted d_c	Residual
(Years)	(MPa)	(mm)	(mm)	(mm)	(mm)
0.01		0.1	0.1	0.1	0.0
15	49.4	7	7	5.7	1.3
15	49.4*	7	7	5.7	1.3
16	42.5	4	4	5.9	-1.9
17	46.38	8	8	6.1	1.9
17	46.38*	7	7	6.1	0.9
17	43.8*	5	5	6.1	-1.1
17	43.8	4	4	6.1	-2.1
17	43.3	9	9	6.1	2.9
17	43.3	10	10	6.1	3.9
20	44.4*	4	4	6.7	-2.7
20	44.4	5	5	6.7	-1.7
22	45*	8	8	7.1	0.9
22	45	8	8	7.1	0.9
33	40.5	8	8	8.8	-0.8
33	40.5	9	9	8.8	0.2
33	48.8	13	13	8.8	4.2
41	41.6	7	7	10.0	-3.0
				Mean	**0.3**
				Std. Dev.	**2.1**
				+2x (Std. Dev.)	**4.3**
				-2x (Std. Dev.)	**-4.3**

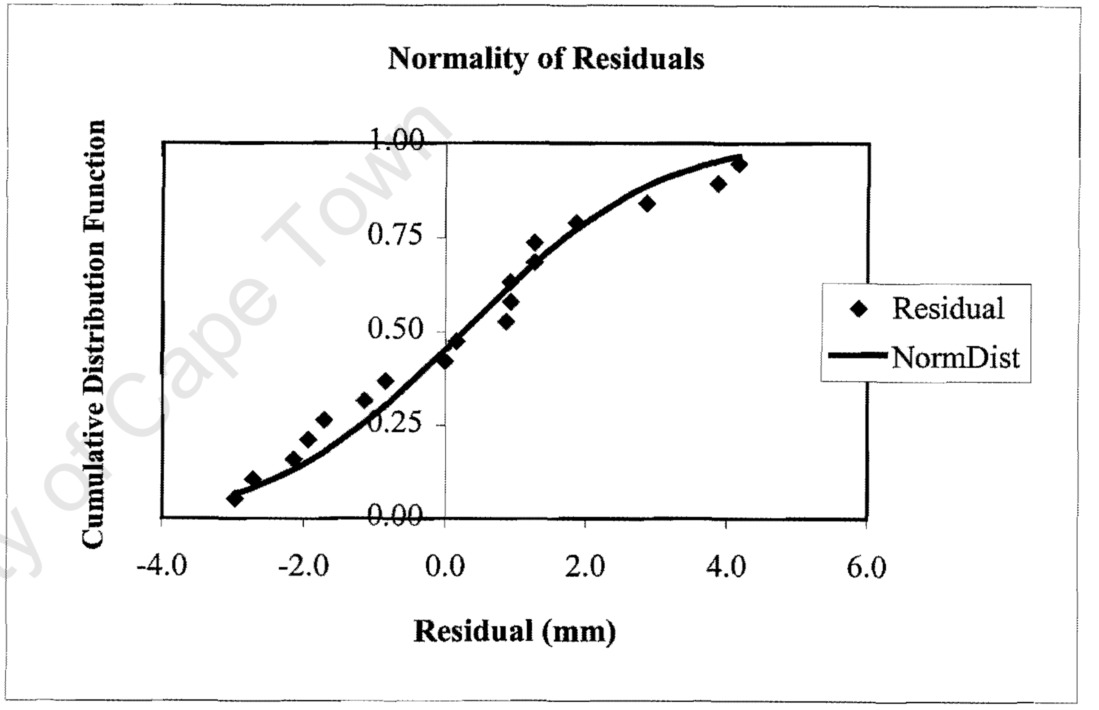
Note: * refers to assumed value

No. of Results: 17



Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)
Method of Analysis: Power Regression on Field Data (Normality of Residuals)
(After the 2nd Elimination of Gross Outliers)

Residual (mm)	Residual (sorted)	Rank (-)	Probability (P<d)	NormDist (-)
0.0	-3.0	1	0.05	0.07
1.3	-2.7	2	0.11	0.08
1.3	-2.1	3	0.16	0.13
-1.9	-1.9	4	0.21	0.15
1.9	-1.7	5	0.26	0.18
0.9	-1.1	6	0.32	0.26
-1.1	-0.8	7	0.37	0.30
-2.1	0.0	8	0.42	0.45
2.9	0.2	9	0.47	0.48
3.9	0.9	10	0.53	0.61
-2.7	0.9	11	0.58	0.62
-1.7	0.9	12	0.63	0.62
0.9	1.3	13	0.68	0.68
0.9	1.3	14	0.74	0.68
-0.8	1.9	15	0.79	0.77
0.2	2.9	16	0.84	0.89
4.2	3.9	17	0.89	0.95
-3.0	4.2	18	0.95	0.97



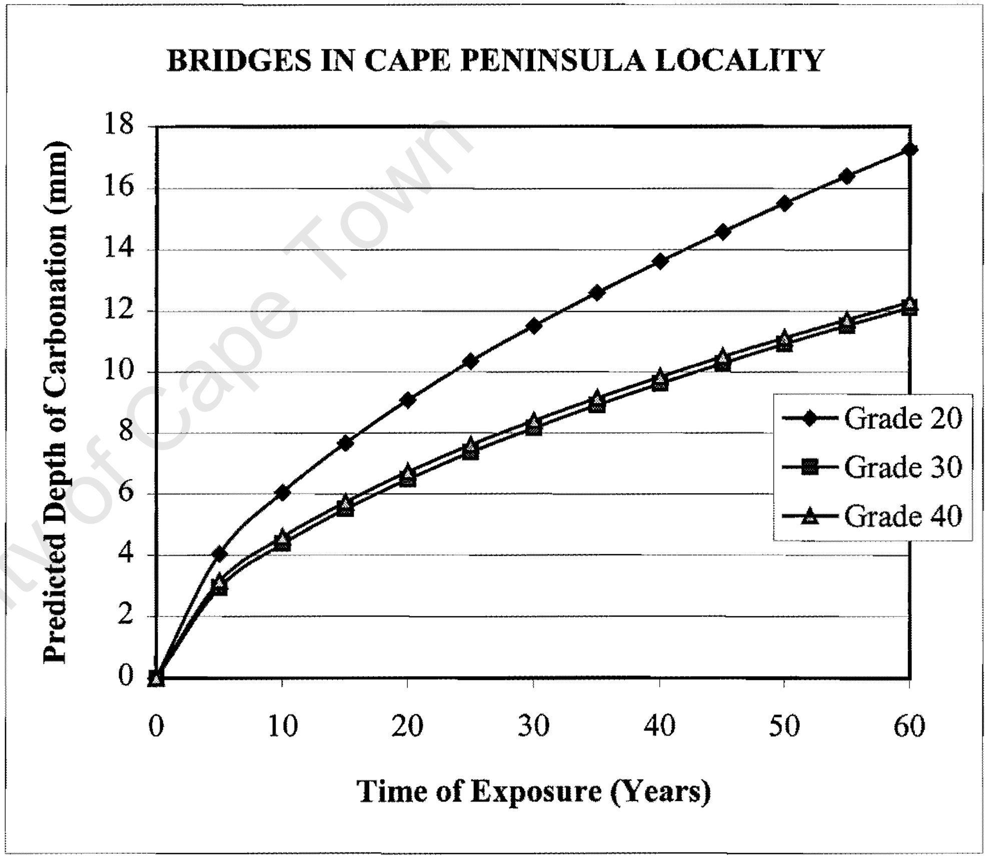
Note: values in bold are gross outliers

BRIDGES OF CAPE PENINSULA

Comparison of Carbonation Prediction Models

Method of Analysis: Power Regression on Field Data

Time	Depth of Carbonation, d_c, (mm)		
(t)	Grade 20	Grade 30	Grade 40
(Years)	$d_c = 1.579t^{0.584}$	$d_c = 1.174t^{0.570}$	$d_c = 1.293t^{0.550}$
0	0.0	0.0	0.0
5	4.0	2.9	3.1
10	6.1	4.4	4.6
15	7.7	5.5	5.7
20	9.1	6.5	6.7
25	10.3	7.4	7.6
30	11.5	8.2	8.4
35	12.6	8.9	9.1
40	13.6	9.6	9.8
45	14.6	10.3	10.5
50	15.5	10.9	11.1
55	16.4	11.5	11.7
60	17.3	12.1	12.3
65	18.1	12.7	12.8



APPENDIX C

ANALYSIS OF CAPE PENINSULA BRIDGE DATA AND EARLY AGE LABORATORY DATA

(Bridge data were provided by Mr. Philip Ronne, and the laboratory data were obtained from Mackechnie (1999))

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with compressive strengths: 21-30 MPa at 28 days)

Method of Analysis: Incorporation of Early Age Lab Data

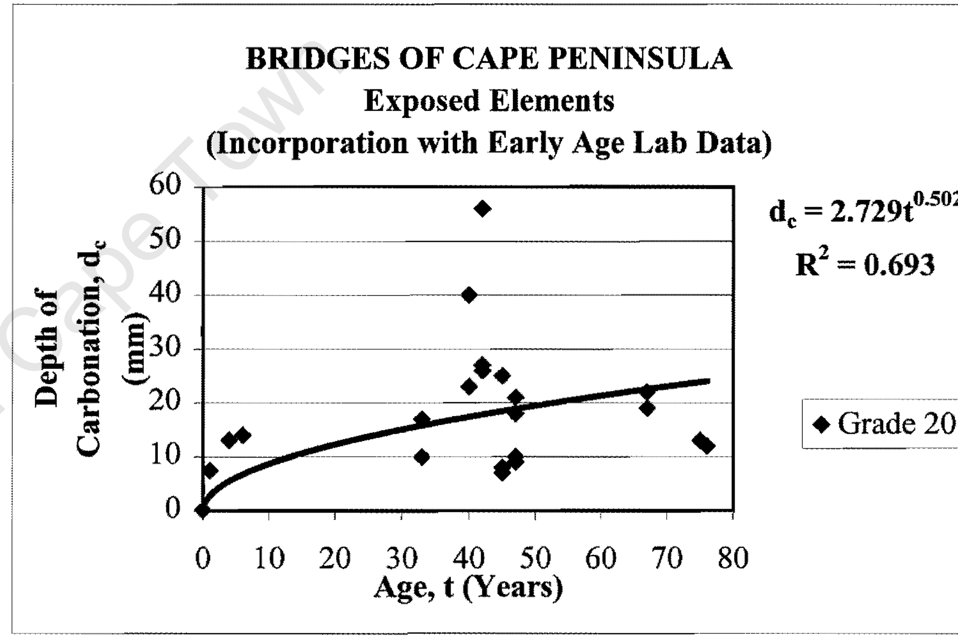
Data Analysis			Detection of Gross Outliers		
Age (t)	Strength	d_c	Measured d_c	Predicted d_c	Residual
(Years)	(MPa)	(mm)	(mm)	(mm)	(mm)
0.01		0.1	0.1	0.3	-0.2
1	20	7.5	7.5	2.7	4.8
4	20	13	13	5.5	7.5
6	20	14	14	6.7	7.3
33	27.7*	17	17	15.8	1.2
33	27.7	10	10	15.8	-5.8
40	30	40	40	17.4	22.6
40	30*	23	23	17.4	5.6
42	23.1	27	27	17.8	9.2
42	**30***	**56**	**56**	**17.8**	**38.2**
42	30	26	26	17.8	8.2
45	26.1	25	25	18.4	6.6
45	30*	8	8	18.4	-10.4
45	30*	7	7	18.4	-11.4
47	22.5	9	9	18.9	-9.9
47	30*	18	18	18.9	-0.9
47	30*	10	10	18.9	-8.9
47	30*	21	21	18.9	2.1
67	30*	19	19	22.5	-3.5
67	30*	22	22	22.5	-0.5
75	30*	13	13	23.8	-10.8
76	30*	12	12	24.0	-12.0
				Mean	**1.8**
				Std. Dev.	**11.9**
				+2x (Std. Dev.)	**23.9**
				-2x (Std. Dev.)	**-23.9**

Note: values in bold are gross outliers

* refers to assumed value

No. of Bridge data: 18

No. of Lab Samples: 3



Note: In order to simplify the procedures for gross outlier detection, all residuals are assumed to be (approximately) normally distributed (for all three localities) based on previous analysis

BRIDGES OF CAPE PENINSULA

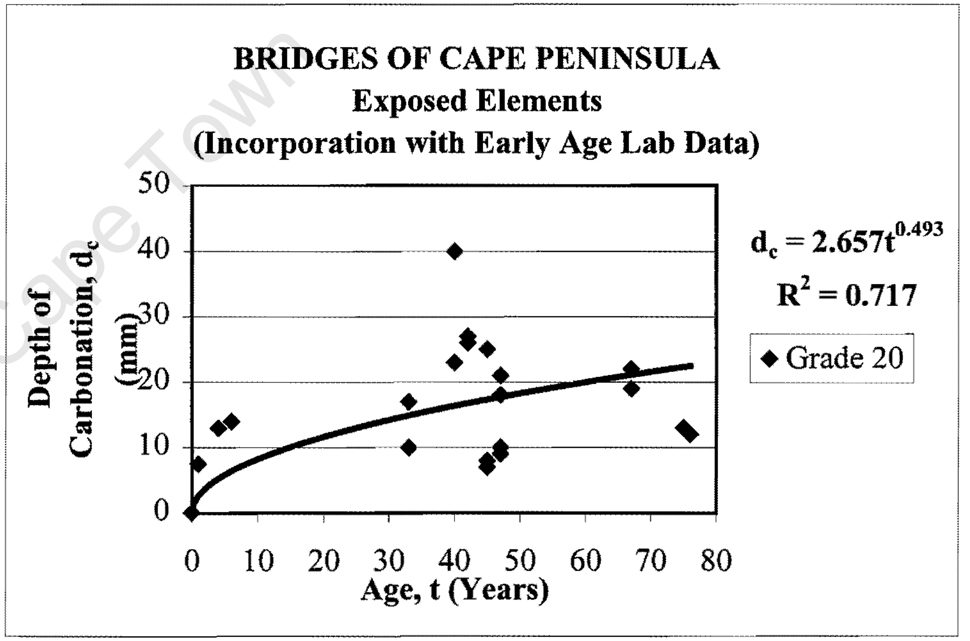
Grade 20 (Exposed Elements with compressive strengths: 21-30 MPa at 28 days)

Method of Analysis: Incorporation of Early Age Lab Data
(After the 1st Elimination of Gross Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Measured d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.3	-0.2
1	20	7.5	7.5	2.7	4.8
4	20	13	13	5.3	7.7
6	20	14	14	6.4	7.6
33	27.7*	17	17	14.9	2.1
33	27.7	10	10	14.9	-4.9
40	**30**	**40**	**40**	**16.4**	**23.6**
40	30*	23	23	16.4	6.6
42	23.1	27	27	16.8	10.2
42	30	26	26	16.8	9.2
45	26.1	25	25	17.4	7.6
45	30*	8	8	17.4	-9.4
45	30*	7	7	17.4	-10.4
47	22.5	9	9	17.7	-8.7
47	30*	18	18	17.7	0.3
47	30*	10	10	17.7	-7.7
47	30*	21	21	17.7	3.3
67	30*	19	19	21.1	-2.1
67	30*	22	22	21.1	0.9
75	30*	13	13	22.3	-9.3
76	30*	12	12	22.5	-10.5

Mean	**1.0**
Std. Dev.	**8.8**
+2x (Std. Dev.)	**17.6**
-2x (Std. Dev.)	**-17.6**

Note: values in bold are gross outliers
* refers to assumed value
No. of Bridge data: 17
No. of Lab Samples: 3



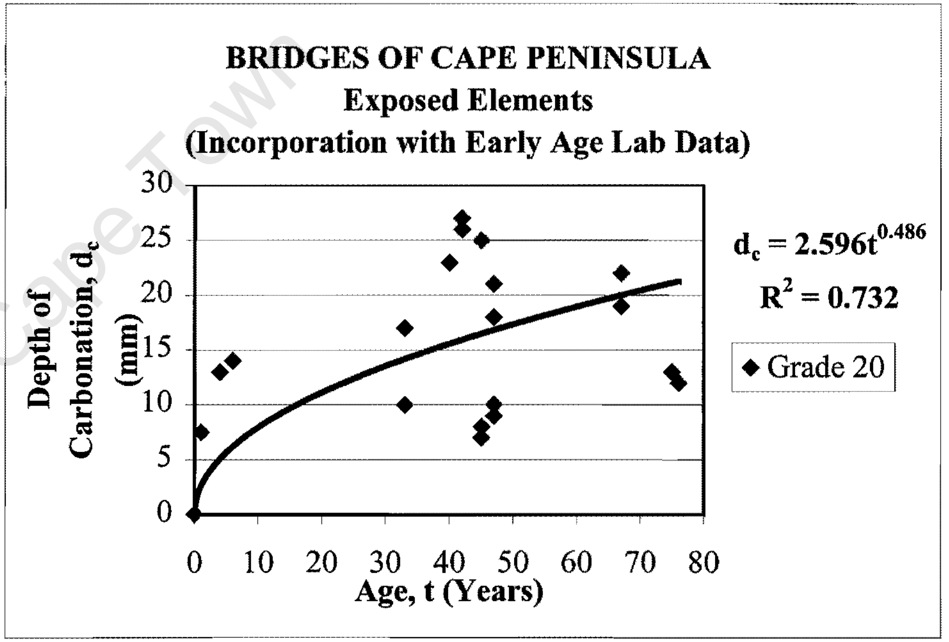
BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with compressive strengths: 21-30 MPa at 28 days)

Method of Analysis: Incorporation of Early Age Lab Data
(After the 2nd Elimination of Gross Outliers)

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Measured d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.3	-0.2
1	20	7.5	7.5	2.6	4.9
4	20	13	13	5.1	7.9
6	20	14	14	6.2	7.8
33	27.7*	17	17	14.2	2.8
33	27.7	10	10	14.2	-4.2
40	30*	23	23	15.6	7.4
42	23.1	27	27	16.0	11.0
42	30	26	26	16.0	10.0
45	26.1	25	25	16.5	8.5
45	30*	8	8	16.5	-8.5
45	30*	7	7	16.5	-9.5
47	22.5	9	9	16.9	-7.9
47	30*	18	18	16.9	1.1
47	30*	10	10	16.9	-6.9
47	30*	21	21	16.9	4.1
67	30*	19	19	20.0	-1.0
67	30*	22	22	20.0	2.0
75	30*	13	13	21.2	-8.2
76	30*	12	12	21.3	-9.3
				Mean	**0.6**
				Std. Dev.	**7.1**
				+2x (Std. Dev.)	**14.2**
				-2x (Std. Dev.)	**-14.2**

Note:* refers to assumed value
No. of Bridge data: 16
No. of Lab Samples: 3



Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data

Data Analysis			Detection of Gross Outliers		
Age (t)	**Strength**	**d_c**	**Observed d_c**	**Predicted d_c**	**Residual**
(Years)	**(MPa)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
0.01		0.1	0.1	0.2	-0.1
1	40	4.5	4.5	1.6	2.9
4	40	5	5	3.3	1.7
6	40	6.5	6.5	4.0	2.5
33	39.4	8	8	9.6	-1.6
33	32.2	10	10	9.6	0.4
33	**32.2***	**18**	**18**	**9.6**	**8.4**
33	39.2*	5	5	9.6	-4.6
33	39.2	6	6	9.6	-3.6
33	39.2	9	9	9.6	-0.6
17	34*	4	4	6.8	-2.8
17	34	8	8	6.8	1.2
17	40*	4	4	6.8	-2.8
17	40*	4	4	6.8	-2.8
34	36.1	9	9	9.7	-0.7
34	36.1*	10	10	9.7	0.3
34	38.3	11	11	9.7	1.3
34	38.3*	15	15	9.7	5.3
34	35*	6	6	9.7	-3.7
40	40*	13	13	10.6	2.4
40	36.9	16	16	10.6	5.4
42	**34.4**	**20**	**20**	**10.8**	**9.2**
42	30.8	16	16	10.8	5.2
43	39.4	12	12	11.0	1.0
43	**39.4***	**20**	**20**	**11.0**	**9.0**
45	38.3	6	6	11.2	-5.2
45	38.3*	17	17	11.2	5.8
67	31.1	11	11	13.7	-2.7
42	33.3	12	12	10.8	1.2
42	33.3*	17	17	10.8	6.2
42	36.9	7	7	10.8	-3.8
42	36.9*	11	11	10.8	0.2
16	32.2	7	7	6.6	0.4
25	35.6*	4	4	8.3	-4.3
25	35.6	3	3	8.3	-5.3
44	30.8*	12	12	11.1	0.9
44	30.8	13	13	11.1	1.9
				Mean	**0.8**
				Std. Dev.	**4.0**
				+2x (Std. Dev.)	**8.0**
				-2x (Std. Dev.)	**-8.0**

Note: values in bold are gross outliers
* refers to assumed value

No. of bridge data: 33
No. of Lab Samples: 3

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data

Data Analysis			**Detection of Gross Outliers**		
Age (t)	**Strength**	**d_c**	**Observed d_c**	**Predicted d_c**	**Residual**
(Years)	**(MPa)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
0.01		0.1	0.1	0.2	-0.1
1	40	4.5	4.5	1.6	2.9
4	40	5	5	3.2	1.8
6	40	6.5	6.5	3.9	2.6
33	39.4	8	8	9.0	-1.0
33	32.2	10	10	9.0	1.0
33	39.2*	5	5	9.0	-4.0
33	39.2	6	6	9.0	-3.0
33	39.2	9	9	9.0	0.0
17	34*	4	4	6.5	-2.5
17	34	8	8	6.5	1.5
17	40*	4	4	6.5	-2.5
17	40*	4	4	6.5	-2.5
34	36.1	9	9	9.1	-0.1
34	36.1*	10	10	9.1	0.9
34	38.3	11	11	9.1	1.9
34	38.3*	15	15	9.1	5.9
34	35*	6	6	9.1	-3.1
40	40*	13	13	9.9	3.1
40	36.9	16	16	9.9	6.1
42	30.8	16	16	10.2	5.8
43	39.4	12	12	10.3	1.7
45	38.3	6	6	10.5	-4.5
45	38.3*	17	17	10.5	6.5
67	31.1	11	11	12.8	-1.8
42	33.3	12	12	10.2	1.8
42	33.3*	17	17	10.2	6.8
42	36.9	7	7	10.2	-3.2
42	36.9*	11	11	10.2	0.8
16	32.2	7	7	6.3	0.7
25	35.6*	4	4	7.8	-3.8
25	35.6	3	3	7.8	-4.8
44	30.8*	12	12	10.4	1.6
44	30.8	13	13	10.4	2.6

Note: *refers to assumed value

Mean	**0.6**
Std. Dev.	**3.3**
+2x (Std. Dev.)	**6.6**
-2x (Std. Dev.)	**-6.6**

No. of bridge data: 30
No. of Lab Samples: 3

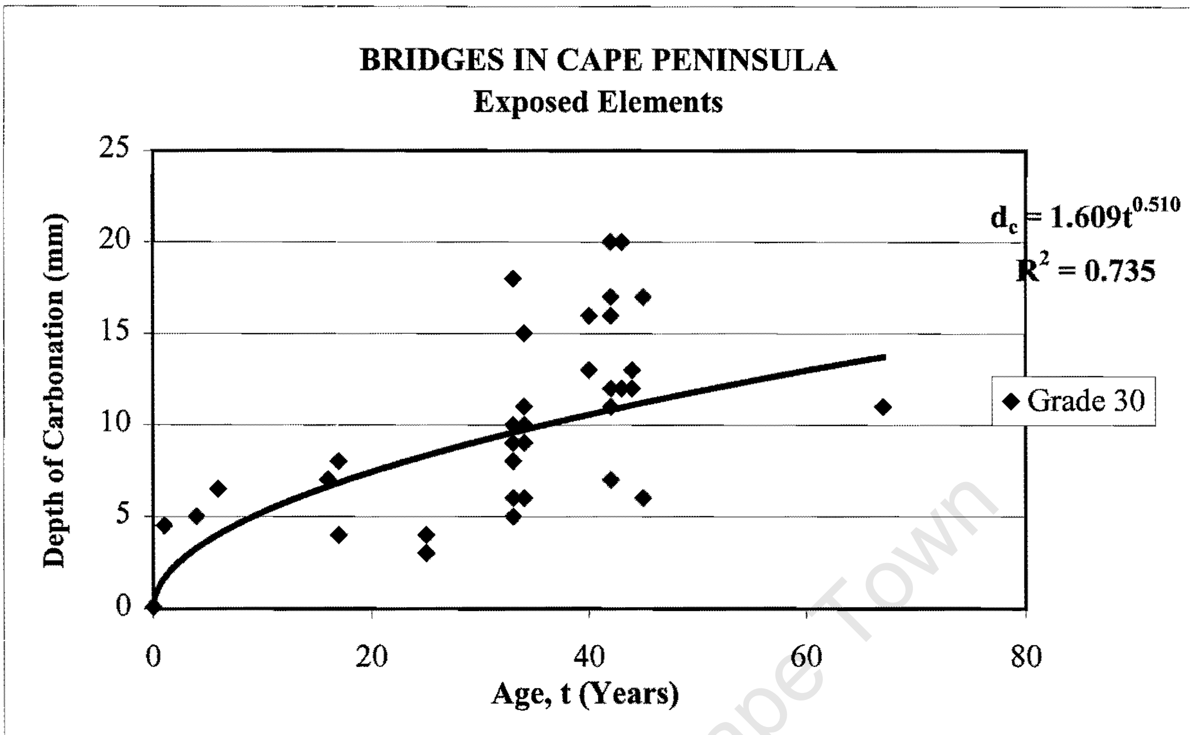
Note: Only one elimination of gross outliers is carried out in this special case because the continuous elimination would reject the whole population group of high carbonation depths (same as previous power regression analysis of field data)

BRIDGES OF CAPE PENINSULA

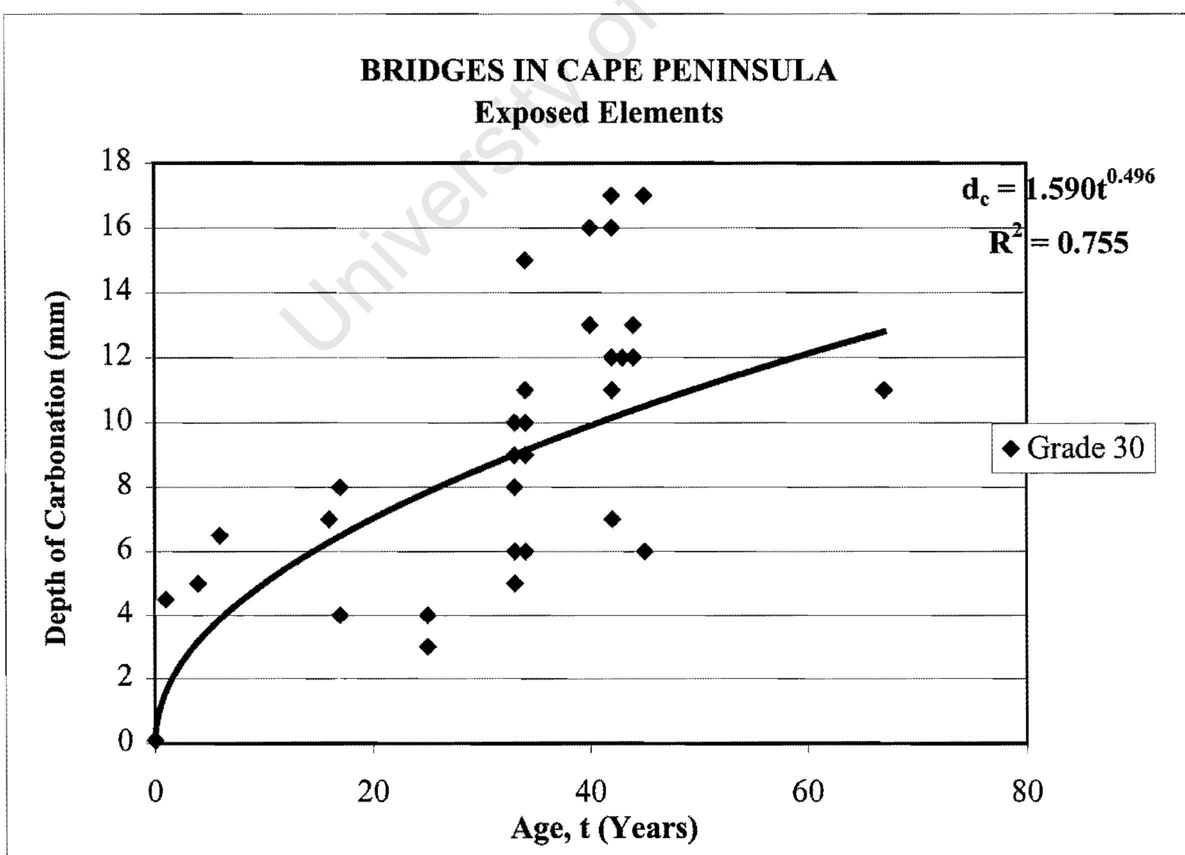
Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data

1. Before the Elimination of Gross Outliers



2. After the 1st Elimination of Gross Outliers



BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.2	-0.1
1	40	4.5	4.5	1.7	2.8
4	40	5	5	3.5	1.5
6	40	6.5	6.5	4.4	2.1
15	49.4	7	7	7.0	0.0
15	49.4*	7	7	7.0	0.0
16	42.5	4	4	7.2	-3.2
17	46.38	8	8	7.4	0.6
17	46.38*	7	7	7.4	-0.4
17	43.8*	5	5	7.4	-2.4
17	43.8	4	4	7.4	-3.4
17	43.3	9	9	7.4	1.6
17	43.3	10	10	7.4	2.6
20	44.4*	4	4	8.1	-4.1
20	44.4	5	5	8.1	-3.1
22	45*	8	8	8.5	-0.5
22	45	8	8	8.5	-0.5
22	41.6*	15	15	8.5	6.5
22	**41.6**	**18**	**18**	**8.5**	**9.5**
33	40.5	8	8	10.4	-2.4
33	40.5	9	9	10.4	-1.4
33	48.8	13	13	10.4	2.6
33	**48.8***	**19**	**19**	**10.4**	**8.6**
41	41.6	7	7	11.7	-4.7

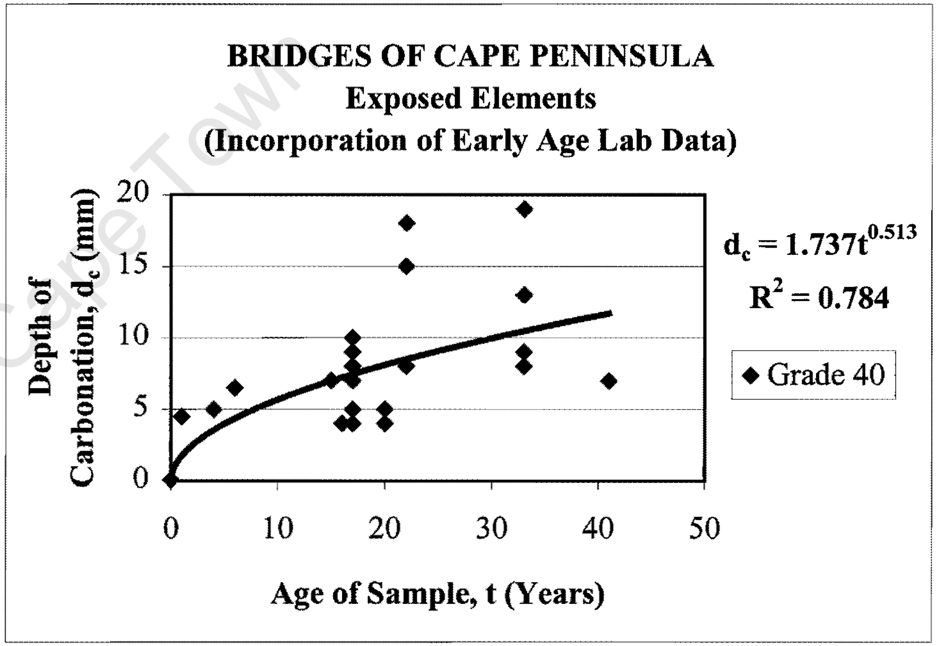
Mean	**0.5**
Stdev	**3.7**
2x (+Stdev)	**7.4**
2x (-Stdev)	**-7.4**

Note: values in bold are gross outliers

* refers to assumed value

No. of bridge data: 20

No. of Lab Samples: 3



BRIDGES OF CAPE PENINSULA

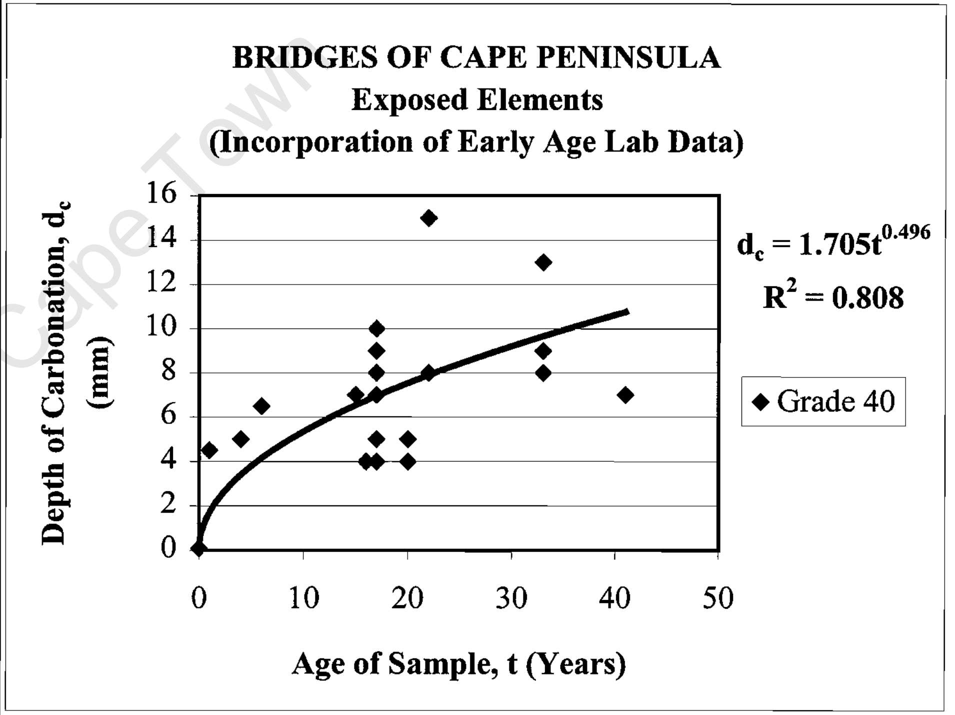
Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data
(After the 1st Elimination of Gross Outliers

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.2	-0.1
1	40	4.5	4.5	1.7	2.8
4	40	5	5	3.4	1.6
6	40	6.5	6.5	4.1	2.4
15	49.4	7	7	6.5	0.5
15	49.4*	7	7	6.5	0.5
16	42.5	4	4	6.7	-2.7
17	46.38	8	8	7.0	1.0
17	46.38*	7	7	7.0	0.0
17	43.8*	5	5	7.0	-2.0
17	43.8	4	4	7.0	-3.0
17	43.3	9	9	7.0	2.0
17	43.3	10	10	7.0	3.0
20	44.4*	4	4	7.5	-3.5
20	44.4	5	5	7.5	-2.5
22	45*	8	8	7.9	0.1
22	45	8	8	7.9	0.1
22	**41.6***	**15**	**15**	**7.9**	**7.1**
33	40.5	8	8	9.7	-1.7
33	40.5	9	9	9.7	-0.7
33	48.8	13	13	9.7	3.3
41	41.6	7	7	10.8	-3.8
				Mean	**0.2**
				Std. Dev.	**2.7**
				+2x (Std. Dev.)	**5.3**
				-2x (Std. Dev.)	**-5.3**

Note: values in bold are gross outliers
* refers to assumed value

No. of bridge data: 18
No. of Lab Samples: 3



BRIDGES OF CAPE PENINSULA

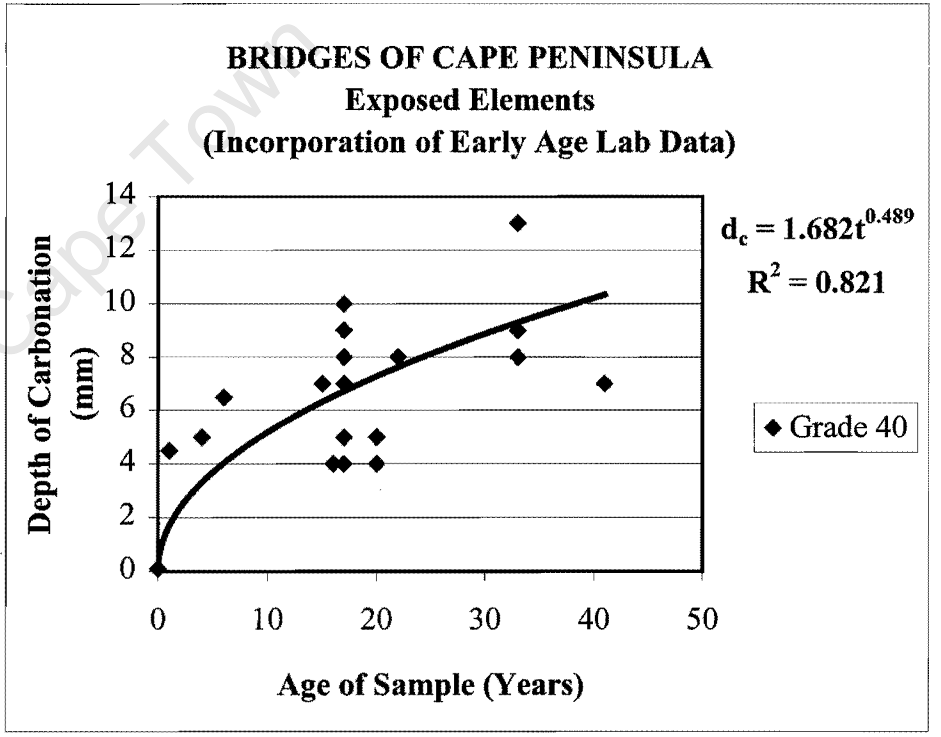
Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 Days)

Method of Analysis: Incorporation of Early Age Lab Data
(After the 2nd Elimination of Gross Outliers

Data Analysis			Detection of Gross Outliers		
Age (t) (Years)	Strength (MPa)	d_c (mm)	Observed d_c (mm)	Predicted d_c (mm)	Residual (mm)
0.01		0.1	0.1	0.2	-0.1
1	40	4.5	4.5	1.7	2.8
4	40	5	5	3.3	1.7
6	40	6.5	6.5	4.0	2.5
15	49.4	7	7	6.3	0.7
15	49.4*	7	7	6.3	0.7
16	42.5	4	4	6.5	-2.5
17	46.38	8	8	6.7	1.3
17	46.38*	7	7	6.7	0.3
17	43.8*	5	5	6.7	-1.7
17	43.8	4	4	6.7	-2.7
17	43.3	9	9	6.7	2.3
17	43.3	10	10	6.7	3.3
20	44.4*	4	4	7.3	-3.3
20	44.4	5	5	7.3	-2.3
22	45*	8	8	7.6	0.4
22	45	8	8	7.6	0.4
33	40.5	8	8	9.3	-1.3
33	40.5	9	9	9.3	-0.3
33	48.8	13	13	9.3	3.7
41	41.6	7	7	10.3	-3.3
				Mean	**0.1**
				Std. Dev.	**2.2**
				+2x (Std. Dev.)	**4.4**
				-2x (Std. Dev.)	**-4.4**

* refers to assumed value

No. of bridge data: 17
No. of Lab Samples: 3

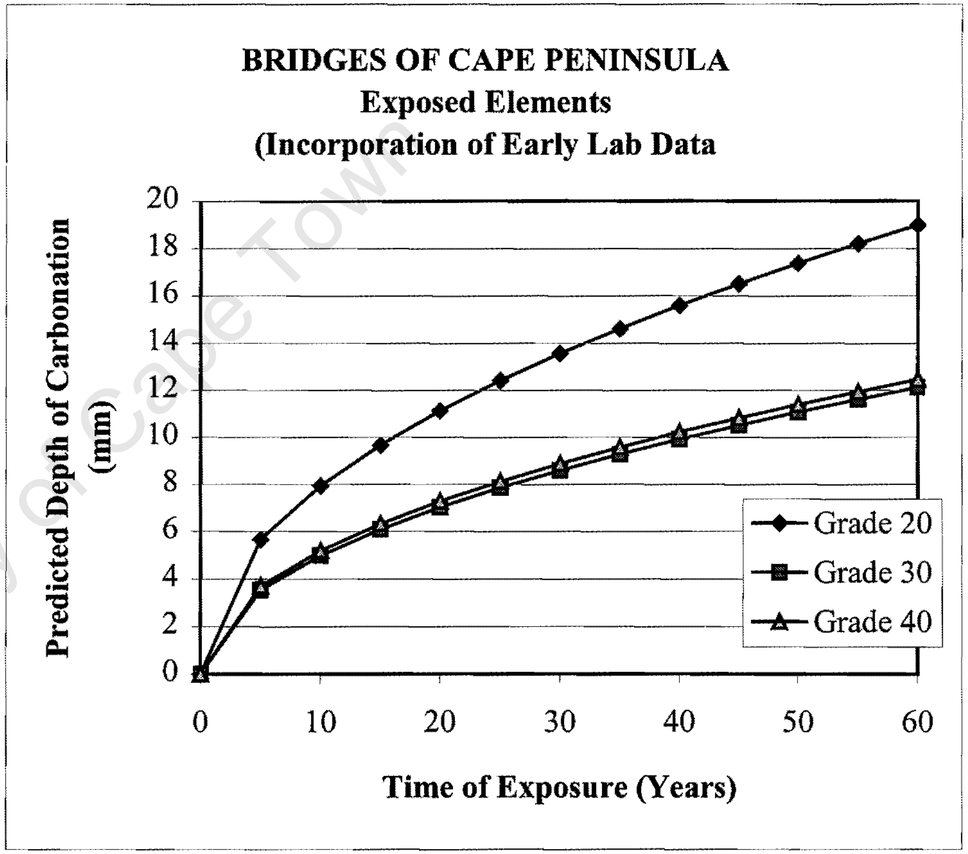


BRIDGES IN CAPE PENINSULA

Comparison of Carbonation Prediction Models

Method of Analysis: Incorporation of Early Age Lab Data

Time	Depth of Carbonation, d_c, (mm)		
(t)	Grade 20	Grade 30	Grade 40
(Years)	$d_c = 2.596t^{0.486}$	$d_c = 1.590t^{0.496}$	$d_c = 1.682t^{0.489}$
0	0.0	0.0	0.0
5	5.7	3.5	3.7
10	7.9	5.0	5.2
15	9.7	6.1	6.3
20	11.1	7.0	7.3
25	12.4	7.8	8.1
30	13.6	8.6	8.9
35	14.6	9.3	9.6
40	15.6	9.9	10.2
45	16.5	10.5	10.8
50	17.4	11.1	11.4
55	18.2	11.6	11.9
60	19.0	12.1	12.5



APPENDIX D

ANALYSIS OF CAPE PENINSULA DATA USING THE METHOD OF LEAST SQUARES

(Data were provided by Mr. Philip Ronne)

The principle of the method of least squares is to optimise the k value (having chosen a value of n) which can minimize the sum of squares of the residuals (difference between d_c of real site data and predicted d_c given by the chosen model). Mathematically,

Residual = $d_{ci} - (kt_i^n)$ where d_{ci} is the depth of carbonation of the elements of bridges measured at time t_i

Square of the residual = $[d_{ci} - (kt_i^n)]^2$

Sum of the squares of the residuals = S = $\sum_{i=1}^{n} [d_{ci} - (kt_i^n)]^2$

In order to minimize the sum of the squares of the residuals, S, put $\dfrac{dS}{dk} = 0$

$$\frac{dS}{dk} = \sum_{i=1}^{n} 2(d_{ci} - kt_i^n)(-t_i^n) = 0$$

$$\sum_{i=1}^{n} t_i^n (d_{ci} - kt_i^n) = 0$$

$$\sum_{i=1}^{n} (d_{ci}\, t_i^n - kt_i^{2n}) = 0$$

$$\{\sum_{i=1}^{n} d_{ci}\, t_i^n\} - k\, \{\sum_{i=1}^{n} t_i^{2n}\} = 0$$

$$\therefore k = \frac{\sum_{i=1}^{n} d_{ci} t_i^n}{\sum_{i=1}^{n} t_i^{2n}}$$

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.3**

$d_c = kt^{0.3}$

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\ t_i^{0.3}$	Predicted	Residual	Residual^2
33	27.7*	17	2.85	8.15	48.53	17.8	-0.8	0.6
33	27.7	10	2.85	8.15	28.55	17.8	-7.8	60.5
40	30	40	3.02	9.15	120.97	18.8	21.2	448.0
40	30*	23	3.02	9.15	69.56	18.8	4.2	17.4
42	23.1	27	3.07	9.42	82.86	19.1	7.9	62.2
42	**30***	**56**	**3.07**	**9.42**	**171.86**	**19.1**	**36.9**	**1360.7**
42	30	26	3.07	9.42	79.79	19.1	6.9	47.4
45	26.1	25	3.13	9.82	78.33	19.5	5.5	30.1
45	30*	8	3.13	9.82	25.06	19.5	-11.5	132.5
45	30*	7	3.13	9.82	21.93	19.5	-12.5	156.5
47	22.5	9	3.17	10.08	28.57	19.8	-10.8	115.9
47	30*	18	3.17	10.08	57.13	19.8	-1.8	3.1
47	30*	10	3.17	10.08	31.74	19.8	-9.8	95.4
47	30*	21	3.17	10.08	66.66	19.8	1.2	1.5
67	30*	19	3.53	12.46	67.08	22.0	-3.0	8.9
67	30*	22	3.53	12.46	77.67	22.0	0.0	0.0
75	30*	13	3.65	13.34	47.47	22.7	-9.7	94.9
76	30*	12	3.67	13.44	44.00	22.8	-10.8	117.4
			Sum	**184.30**	**1147.75**	**Mean**	**0.3**	
						Std. Dev.	**12.7**	
						+2x(Std. Dev.	**25.4**	
						-2x(Std. Dev.)	**-25.4**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	**6.23**

Sum of Residual^2	**2753.2**

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	**0.3**

$d_c = kt^{0.3}$

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\, t_i^{0.3}$	Predicted	Residual	Residual^2
33	27.7*	17	2.85	8.15	48.53	15.9	1.1	1.1
33	27.7	10	2.85	8.15	28.55	15.9	-5.9	35.2
40	**30**	**40**	**3.02**	**9.15**	**120.97**	**16.9**	**23.1**	**534.7**
40	30*	23	3.02	9.15	69.56	16.9	6.1	37.5
42	23.1	27	3.07	9.42	82.86	17.1	9.9	97.5
42	30	26	3.07	9.42	79.79	17.1	8.9	78.8
45	26.1	25	3.13	9.82	78.33	17.5	7.5	56.5
45	30*	8	3.13	9.82	25.06	17.5	-9.5	89.9
45	30*	7	3.13	9.82	21.93	17.5	-10.5	109.9
47	22.5	9	3.17	10.08	28.57	17.7	-8.7	75.9
47	30*	18	3.17	10.08	57.13	17.7	0.3	0.1
47	30*	10	3.17	10.08	31.74	17.7	-7.7	59.5
47	30*	21	3.17	10.08	66.66	17.7	3.3	10.8
67	30*	19	3.53	12.46	67.08	19.7	-0.7	0.5
67	30*	22	3.53	12.46	77.67	19.7	2.3	5.3
75	30*	13	3.65	13.34	47.47	20.4	-7.4	54.4
76	30*	12	3.67	13.44	44.00	20.5	-8.5	71.6
			Sum	**174.88**	**975.89**	**Mean**	**0.2**	
						Std. Dev.	**9.1**	
						+2x(Std. Dev.	**18.2**	
						-2x(Std. Dev.)	**-18.2**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	**5.58**

Sum of Residual^2	**1319.2**

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.3

$d_c = kt^{0.3}$

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\, t_i^{0.3}$	Predicted	Residual	Residual^2
33	27.7*	17	2.85	8.15	48.53	14.7	2.3	5.2
33	27.7	10	2.85	8.15	28.55	14.7	-4.7	22.3
40	30*	23	3.02	9.15	69.56	15.6	7.4	54.8
42	23.1	27	3.07	9.42	82.86	15.8	11.2	124.8
42	30	26	3.07	9.42	79.79	15.8	10.2	103.4
45	26.1	25	3.13	9.82	78.33	16.2	8.8	78.1
45	30*	8	3.13	9.82	25.06	16.2	-8.2	66.6
45	30*	7	3.13	9.82	21.93	16.2	-9.2	83.9
47	22.5	9	3.17	10.08	28.57	16.4	-7.4	54.4
47	30*	18	3.17	10.08	57.13	16.4	1.6	2.6
47	30*	10	3.17	10.08	31.74	16.4	-6.4	40.6
47	30*	21	3.17	10.08	66.66	16.4	4.6	21.4
67	30*	19	3.53	12.46	67.08	18.2	0.8	0.6
67	30*	22	3.53	12.46	77.67	18.2	3.8	14.4
75	30*	13	3.65	13.34	47.47	18.8	-5.8	34.1
76	30*	12	3.67	13.44	44.00	18.9	-6.9	47.8
			Sum	**165.74**	**854.92**	**Mean**	**0.1**	
						Std. Dev.	**7.1**	
						+2x(Std. Dev.	**14.2**	
						-2x(Std. Dev.)	**-14.2**	

Note: * refers to assumed value

No. of Results: 16

k	5.16

Sum of Residual^2	755.0

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.4**

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
33	27.7*	17	4.05	16.40	68.84	17.0	0.0	0.0
33	27.7	10	4.05	16.40	40.50	17.0	-7.0	48.7
40	30	40	4.37	19.13	174.94	18.3	21.7	469.3
40	30*	23	4.37	19.13	100.59	18.3	4.7	21.8
42	23.1	27	4.46	19.89	120.41	18.7	8.3	68.9
42	**30***	**56**	4.46	19.89	**249.74**	18.7	**37.3**	**1391.5**
42	30	26	4.46	19.89	115.95	18.7	7.3	53.3
45	26.1	25	4.58	21.02	114.61	19.2	5.8	33.4
45	30*	8	4.58	21.02	36.68	19.2	-11.2	125.9
45	30*	7	4.58	21.02	32.09	19.2	-12.2	149.3
47	22.5	9	4.66	21.76	41.98	19.6	-10.6	111.5
47	30*	18	4.66	21.76	83.97	19.6	-1.6	2.4
47	30*	10	4.66	21.76	46.65	19.6	-9.6	91.4
47	30*	21	4.66	21.76	97.96	19.6	1.4	2.1
67	30*	19	5.38	28.90	102.14	22.5	-3.5	12.5
67	30*	22	5.38	28.90	118.26	22.5	-0.5	0.3
75	30*	13	5.62	31.63	73.11	23.6	-10.6	111.9
76	30*	12	5.65	31.96	67.84	23.7	-11.7	137.0
			Sum	**402.20**	**1686.26**	**Mean**	**0.4**	
						Std. Dev.	**12.9**	
						+2x(Std. Dev.	**25.8**	
						-2x(Std. Dev.)	**-25.8**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	**4.19**

Sum of Residual^2	**2831.2**

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
33	27.7*	17	4.05	16.40	68.84	15.2	1.8	3.2
33	27.7	10	4.05	16.40	40.50	15.2	-5.2	27.2
40	**30**	**40**	**4.37**	**19.13**	**174.94**	**16.4**	**23.6**	**555.4**
40	30*	23	4.37	19.13	100.59	16.4	6.6	43.1
42	23.1	27	4.46	19.89	120.41	16.8	10.2	104.9
42	30	26	4.46	19.89	115.95	16.8	9.2	85.4
45	26.1	25	4.58	21.02	114.61	17.2	7.8	60.4
45	30*	8	4.58	21.02	36.68	17.2	-9.2	85.1
45	30*	7	4.58	21.02	32.09	17.2	-10.2	104.6
47	22.5	9	4.66	21.76	41.98	17.5	-8.5	72.7
47	30*	18	4.66	21.76	83.97	17.5	0.5	0.2
47	30*	10	4.66	21.76	46.65	17.5	-7.5	56.7
47	30*	21	4.66	21.76	97.96	17.5	3.5	12.1
67	30*	19	5.38	28.90	102.14	20.2	-1.2	1.4
67	30*	22	5.38	28.90	118.26	20.2	1.8	3.2
75	30*	13	5.62	31.63	73.11	21.1	-8.1	66.1
76	30*	12	5.65	31.96	67.84	21.2	-9.2	85.4
			Sum	**382.31**	**1436.52**	**Mean**	**0.3**	
						Std. Dev.	**9.2**	
						+2x(Std. Dev.	**18.5**	
						-2x(Std. Dev.)	**-18.5**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	3.76

Sum of Residual^2	1367.3

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
33	27.7*	17	4.05	16.40	68.84	14.1	2.9	8.6
33	27.7	10	4.05	16.40	40.50	14.1	-4.1	16.5
40	30*	23	4.37	19.13	100.59	15.2	7.8	61.0
42	23.1	27	4.46	19.89	120.41	15.5	11.5	132.4
42	30	26	4.46	19.89	115.95	15.5	10.5	110.4
45	26.1	25	4.58	21.02	114.61	15.9	9.1	82.4
45	30*	8	4.58	21.02	36.68	15.9	-7.9	62.8
45	30*	7	4.58	21.02	32.09	15.9	-8.9	79.7
47	22.5	9	4.66	21.76	41.98	16.2	-7.2	51.9
47	30*	18	4.66	21.76	83.97	16.2	1.8	3.2
47	30*	10	4.66	21.76	46.65	16.2	-6.2	38.5
47	30*	21	4.66	21.76	97.96	16.2	4.8	23.0
67	30*	19	5.38	28.90	102.14	18.7	0.3	0.1
67	30*	22	5.38	28.90	118.26	18.7	3.3	11.1
75	30*	13	5.62	31.63	73.11	19.5	-6.5	42.7
76	30*	12	5.65	31.96	67.84	19.6	-7.6	58.4
			Sum	**363.18**	**1261.58**	**Mean**	**0.2**	
						Std. Dev.	**7.2**	
						+2x(Std. Dev.	**14.4**	
						-2x(Std. Dev.)	**-14.4**	

Note: * refers to assumed value

No. of Results: 16

k	3.47

Sum of Residual^2	782.7

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Strength	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
33	27.7*	17	5.74	33.00	97.66	16.2	0.8	0.7
33	27.7	10	5.74	33.00	57.45	16.2	-6.2	38.2
40	30	40	6.32	40.00	252.98	17.8	22.2	492.2
40	30*	23	6.32	40.00	145.46	17.8	5.2	26.9
42	23.1	27	6.48	42.00	174.98	18.3	8.7	76.5
42	**30***	**56**	6.48	42.00	**362.92**	18.3	**37.7**	**1424.7**
42	30	26	6.48	42.00	168.50	18.3	7.7	60.0
45	26.1	25	6.71	45.00	167.71	18.9	6.1	37.3
45	30*	8	6.71	45.00	53.67	18.9	-10.9	118.7
45	30*	7	6.71	45.00	46.96	18.9	-11.9	141.5
47	22.5	9	6.86	47.00	61.70	19.3	-10.3	106.3
47	30*	18	6.86	47.00	123.40	19.3	-1.3	1.7
47	30*	10	6.86	47.00	68.56	19.3	-9.3	86.7
47	30*	21	6.86	47.00	143.97	19.3	1.7	2.9
67	30*	19	8.19	67.00	155.52	23.1	-4.1	16.4
67	30*	22	8.19	67.00	180.08	23.1	-1.1	1.1
75	30*	13	8.66	75.00	112.58	24.4	-11.4	129.8
76	30*	12	8.72	76.00	104.61	24.6	-12.6	157.6
			Sum	**880.00**	**2478.70**	**Mean**	**0.6**	
						Std. Dev.	**13.1**	
						+2x(Std. Dev.	**26.2**	
						-2x(Std. Dev.)	**-26.2**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	2.82

Sum of Residual^2	2919.2

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Strength	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
33	27.7*	17	5.74	33.00	97.66	14.5	2.5	6.2
33	27.7	10	5.74	33.00	57.45	14.5	-4.5	20.3
40	**30**	**40**	**6.32**	**40.00**	**252.98**	**16.0**	**24.0**	**577.5**
40	30*	23	6.32	40.00	145.46	16.0	7.0	49.4
42	23.1	27	6.48	42.00	174.98	16.4	10.6	113.2
42	30	26	6.48	42.00	168.50	16.4	9.6	92.9
45	26.1	25	6.71	45.00	167.71	16.9	8.1	65.0
45	30*	8	6.71	45.00	53.67	16.9	-8.9	79.9
45	30*	7	6.71	45.00	46.96	16.9	-9.9	98.7
47	22.5	9	6.86	47.00	61.70	17.3	-8.3	69.0
47	30*	18	6.86	47.00	123.40	17.3	0.7	0.5
47	30*	10	6.86	47.00	68.56	17.3	-7.3	53.4
47	30*	21	6.86	47.00	143.97	17.3	3.7	13.6
67	30*	19	8.19	67.00	155.52	20.7	-1.7	2.8
67	30*	22	8.19	67.00	180.08	20.7	1.3	1.8
75	30*	13	8.66	75.00	112.58	21.9	-8.9	78.6
76	30*	12	8.72	76.00	104.61	22.0	-10.0	100.2
			Sum	**838.00**	**2115.78**	**Mean**	**0.5**	
						Std. Dev.	**9.4**	
						+2x(Std. Dev.	**18.8**	
						-2x(Std. Dev.)	**-18.8**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	2.52

Sum of Residual^2	1423.1

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Strength	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
33	27.7*	17	5.74	33.00	97.66	13.4	3.6	12.9
33	27.7	10	5.74	33.00	57.45	13.4	-3.4	11.6
40	30*	23	6.32	40.00	145.46	14.8	8.2	67.8
42	23.1	27	6.48	42.00	174.98	15.1	11.9	140.9
42	30	26	6.48	42.00	168.50	15.1	10.9	118.2
45	26.1	25	6.71	45.00	167.71	15.7	9.3	87.3
45	30*	8	6.71	45.00	53.67	15.7	-7.7	58.7
45	30*	7	6.71	45.00	46.96	15.7	-8.7	75.0
47	22.5	9	6.86	47.00	61.70	16.0	-7.0	49.0
47	30*	18	6.86	47.00	123.40	16.0	2.0	4.0
47	30*	10	6.86	47.00	68.56	16.0	-6.0	36.0
47	30*	21	6.86	47.00	143.97	16.0	5.0	25.0
67	30*	19	8.19	67.00	155.52	19.1	-0.1	0.0
67	30*	22	8.19	67.00	180.08	19.1	2.9	8.4
75	30*	13	8.66	75.00	112.58	20.2	-7.2	52.1
76	30*	12	8.72	76.00	104.61	20.4	-8.4	69.7
			Sum	**798.00**	**1862.80**	**Mean**	**0.3**	
						Std. Dev.	**7.4**	
						+2x(Std. Dev.	**14.7**	
						-2x(Std. Dev.)	**-14.7**	

Note: * refers to assumed value

No. of Results: 16

k	2.33

Sum of Residual^2	816.6

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.6**

$d_c = kt^{0.6}$

Age (t)	Strength	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\, t_i^{0.6}$	Predicted	Residual	Residual^2
33	27.7*	17	8.15	66.41	138.53	15.4	1.6	2.6
33	27.7	10	8.15	66.41	81.49	15.4	-5.4	29.0
40	30	40	9.15	83.65	365.84	17.3	22.7	516.6
40	30*	23	9.15	83.65	210.36	17.3	5.7	32.8
42	23.1	27	9.42	88.70	254.28	17.8	9.2	84.9
42	**30***	**56**	9.42	88.70	**527.40**	17.8	**38.2**	**1460.5**
42	30	26	9.42	88.70	244.86	17.8	8.2	67.5
45	26.1	25	9.82	96.35	245.40	18.5	6.5	41.8
45	30*	8	9.82	96.35	78.53	18.5	-10.5	111.0
45	30*	7	9.82	96.35	68.71	18.5	-11.5	133.1
47	22.5	9	10.08	101.51	90.68	19.0	-10.0	100.5
47	30*	18	10.08	101.51	181.36	19.0	-1.0	1.1
47	30*	10	10.08	101.51	100.75	19.0	-9.0	81.5
47	30*	21	10.08	101.51	211.58	19.0	2.0	3.9
67	30*	19	12.46	155.34	236.81	23.5	-4.5	20.6
67	30*	22	12.46	155.34	274.20	23.5	-1.5	2.4
75	30*	13	13.34	177.86	173.37	25.2	-12.2	148.4
76	30*	12	13.44	180.71	161.31	25.4	-13.4	179.1
			Sum	**1930.55**	**3645.47**	**Mean**	**0.8**	
						Std. Dev.	**13.3**	
						+2x(Std. Dev.	**26.6**	
						-2x(Std. Dev.)	**-26.6**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	**1.89**

Sum of Residual^2	**3017.3**

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.6

$d_c = kt^{0.6}$

Age (t)	Strength	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\ t_i^{0.6}$	Predicted	Residual	Residual^2
33	27.7*	17	8.15	66.41	138.53	13.8	3.2	10.3
33	27.7	10	8.15	66.41	81.49	13.8	-3.8	14.4
40	**30**	**40**	**9.15**	**83.65**	**365.84**	**15.5**	**24.5**	**601.1**
40	30*	23	9.15	83.65	210.36	15.5	7.5	56.5
42	23.1	27	9.42	88.70	254.28	15.9	11.1	122.2
42	30	26	9.42	88.70	244.86	15.9	10.1	101.1
45	26.1	25	9.82	96.35	245.40	16.6	8.4	70.3
45	30*	8	9.82	96.35	78.53	16.6	-8.6	74.3
45	30*	7	9.82	96.35	68.71	16.6	-9.6	92.5
47	22.5	9	10.08	101.51	90.68	17.1	-8.1	64.9
47	30*	18	10.08	101.51	181.36	17.1	0.9	0.9
47	30*	10	10.08	101.51	100.75	17.1	-7.1	49.8
47	30*	21	10.08	101.51	211.58	17.1	3.9	15.6
67	30*	19	12.46	155.34	236.81	21.1	-2.1	4.4
67	30*	22	12.46	155.34	274.20	21.1	0.9	0.8
75	30*	13	13.34	177.86	173.37	22.6	-9.6	91.7
76	30*	12	13.44	180.71	161.31	22.8	-10.8	115.7
			Sum	**1841.86**	**3118.07**	**Mean**	**0.6**	
						Std. Dev.	**9.6**	
						+2x(Std. Dev.	**19.2**	
						-2x(Std. Dev.)	**-19.2**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	1.69

Sum of Residual^2	1486.4

BRIDGES OF CAPE PENINSULA

Grade 20 (Exposed Elements with Compressive Strengths: 21-30 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.6

$d_c = kt^{0.6}$

Age (t)	Strength	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\ t_i^{0.6}$	Predicted	Residual	Residual^2
33	27.7*	17	8.15	66.41	138.53	12.8	4.2	18.0
33	27.7	10	8.15	66.41	81.49	12.8	-2.8	7.6
40	30*	23	9.15	83.65	210.36	14.3	8.7	75.4
42	23.1	27	9.42	88.70	254.28	14.7	12.3	150.3
42	30	26	9.42	88.70	244.86	14.7	11.3	126.7
45	26.1	25	9.82	96.35	245.40	15.4	9.6	92.8
45	30*	8	9.82	96.35	78.53	15.4	-7.4	54.2
45	30*	7	9.82	96.35	68.71	15.4	-8.4	70.0
47	22.5	9	10.08	101.51	90.68	15.8	-6.8	45.9
47	30*	18	10.08	101.51	181.36	15.8	2.2	5.0
47	30*	10	10.08	101.51	100.75	15.8	-5.8	33.3
47	30*	21	10.08	101.51	211.58	15.8	5.2	27.3
67	30*	19	12.46	155.34	236.81	19.5	-0.5	0.3
67	30*	22	12.46	155.34	274.20	19.5	2.5	6.2
75	30*	13	13.34	177.86	173.37	20.9	-7.9	62.0
76	30*	12	13.44	180.71	161.31	21.0	-9.0	81.8
			Sum	**1758.21**	**2752.23**	**Mean**	**0.5**	
						Std. Dev.	**7.5**	
						+2x(Std. Dev.	**15.1**	
						-2x(Std. Dev.)	**-15.1**	

Note: * refers to assumed value

No. of Results: 16

k	1.57

Sum of Residual^2	856.8

BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.3

$d_c = kt^{0.3}$

Age (t)	Strength	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\, t_i^{0.3}$	Predicted	Residual	Residual^2
33	39.4	8	2.85	8.15	22.84	10.5	-2.5	6.3
33	32.2	10	2.85	8.15	28.55	10.5	-0.5	0.3
33	32.2*	18	2.85	8.15	51.38	10.5	7.5	56.2
33	39.2*	5	2.85	8.15	14.27	10.5	-5.5	30.3
33	39.2	6	2.85	8.15	17.13	10.5	-4.5	20.3
33	39.2	9	2.85	8.15	25.69	10.5	-1.5	2.3
17	34*	4	2.34	5.47	9.36	8.6	-4.6	21.2
17	34	8	2.34	5.47	18.72	8.6	-0.6	0.4
17	40*	4	2.34	5.47	9.36	8.6	-4.6	21.2
17	40*	4	2.34	5.47	9.36	8.6	-4.6	21.2
34	36.1	9	2.88	8.30	25.92	10.6	-1.6	2.5
34	36.1*	10	2.88	8.30	28.80	10.6	-0.6	0.4
34	38.3	11	2.88	8.30	31.68	10.6	0.4	0.2
34	38.3*	15	2.88	8.30	43.21	10.6	4.4	19.4
34	35*	6	2.88	8.30	17.28	10.6	-4.6	21.1
40	40*	13	3.02	9.15	39.32	11.1	1.9	3.5
40	36.9	16	3.02	9.15	48.39	11.1	4.9	23.8
42	34.4	20	3.07	9.42	61.38	11.3	8.7	75.9
42	30.8	16	3.07	9.42	49.10	11.3	4.7	22.2
43	39.4	12	3.09	9.55	37.09	11.4	0.6	0.4
43	39.4*	20	3.09	9.55	61.81	11.4	8.6	74.5
45	38.3	6	3.13	9.82	18.80	11.5	-5.5	30.5
45	38.3*	17	3.13	9.82	53.26	11.5	5.5	30.0
67	31.1	11	3.53	12.46	38.83	13.0	-2.0	4.0
42	33.3	12	3.07	9.42	36.83	11.3	0.7	0.5
42	33.3*	17	3.07	9.42	52.17	11.3	5.7	32.6
42	36.9	7	3.07	9.42	21.48	11.3	-4.3	18.4
42	36.9*	11	3.07	9.42	33.76	11.3	-0.3	0.1
16	32.2	7	2.30	5.28	16.08	8.5	-1.5	2.1
25	35.6*	4	2.63	6.90	10.51	9.7	-5.7	32.1
25	35.6	3	2.63	6.90	7.88	9.7	-6.7	44.4
44	30.8*	12	3.11	9.68	37.34	11.4	0.6	0.3
44	30.8	13	3.11	9.68	40.46	11.4	1.6	2.4
			Sum	**276.71**	**1018.03**	**Mean**	**-0.2**	
						Std. Dev.	**4.4**	
						+2x(Std. Dev.)	**8.8**	
						-2x(Std. Dev.)	**-8.8**	

Note: * refers to assumed value

No. of Results: 33

k	3.68

Sum of Residual^2	620.7

BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.4**

$$d_c = kt^{0.4}$$

Age (t)	Strength	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	Predicted	Residual	Residual^2
33	39.4	8	4.05	16.40	32.40	10.5	-2.5	6.0
33	32.2	10	4.05	16.40	40.50	10.5	-0.5	0.2
33	32.2*	18	4.05	16.40	72.89	10.5	7.5	56.9
33	39.2*	5	4.05	16.40	20.25	10.5	-5.5	29.8
33	39.2	6	4.05	16.40	24.30	10.5	-4.5	19.9
33	39.2	9	4.05	16.40	36.45	10.5	-1.5	2.1
17	34*	4	3.11	9.65	12.42	8.0	-4.0	16.2
17	34	8	3.11	9.65	24.85	8.0	0.0	0.0
17	40*	4	3.11	9.65	12.42	8.0	-4.0	16.2
17	40*	4	3.11	9.65	12.42	8.0	-4.0	16.2
34	36.1	9	4.10	16.80	36.88	10.6	-1.6	2.5
34	36.1*	10	4.10	16.80	40.98	10.6	-0.6	0.3
34	38.3	11	4.10	16.80	45.08	10.6	0.4	0.2
34	38.3*	15	4.10	16.80	61.47	10.6	4.4	19.5
34	35*	6	4.10	16.80	24.59	10.6	-4.6	21.0
40	40*	13	4.37	19.13	56.85	11.3	1.7	2.9
40	36.9	16	4.37	19.13	69.98	11.3	4.7	22.1
42	34.4	20	4.46	19.89	89.19	11.5	8.5	72.0
42	30.8	16	4.46	19.89	71.35	11.5	4.5	20.1
43	39.4	12	4.50	20.27	54.02	11.6	0.4	0.1
43	39.4*	20	4.50	20.27	90.04	11.6	8.4	70.1
45	38.3	6	4.58	21.02	27.51	11.8	-5.8	34.1
45	38.3*	17	4.58	21.02	77.94	11.8	5.2	26.6
67	31.1	11	5.38	28.90	59.13	13.9	-2.9	8.3
42	33.3	12	4.46	19.89	53.52	11.5	0.5	0.2
42	33.3*	17	4.46	19.89	75.81	11.5	5.5	30.1
42	36.9	7	4.46	19.89	31.22	11.5	-4.5	20.4
42	36.9*	11	4.46	19.89	49.06	11.5	-0.5	0.3
16	32.2	7	3.03	9.19	21.22	7.8	-0.8	0.7
25	35.6*	4	3.62	13.13	14.50	9.4	-5.4	28.7
25	35.6	3	3.62	13.13	10.87	9.4	-6.4	40.4
44	30.8*	12	4.54	20.64	54.52	11.7	0.3	0.1
44	30.8	13	4.54	20.64	59.06	11.7	1.3	1.6
			Sum	**566.74**	**1463.68**	**Mean**	**-0.2**	
						Std. Dev.	**4.3**	
						+2x(Std. Dev.)	**8.5**	
						-2x(Std. Dev.)	**-8.5**	

Note: * refers to assumed value

No. of Results: 33

k	**2.58**

Sum of Residual^2	**585.9**

BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Strength	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
33	39.4	8	5.74	33.00	45.96	10.4	-2.4	5.7
33	32.2	10	5.74	33.00	57.45	10.4	-0.4	0.1
33	32.2*	18	5.74	33.00	103.40	10.4	7.6	58.0
33	39.2*	5	5.74	33.00	28.72	10.4	-5.4	29.0
33	39.2	6	5.74	33.00	34.47	10.4	-4.4	19.2
33	39.2	9	5.74	33.00	51.70	10.4	-1.4	1.9
17	34*	4	4.12	17.00	16.49	7.5	-3.5	11.9
17	34	8	4.12	17.00	32.98	7.5	0.5	0.3
17	40*	4	4.12	17.00	16.49	7.5	-3.5	11.9
17	40*	4	4.12	17.00	16.49	7.5	-3.5	11.9
34	36.1	9	5.83	34.00	52.48	10.5	-1.5	2.4
34	36.1*	10	5.83	34.00	58.31	10.5	-0.5	0.3
34	38.3	11	5.83	34.00	64.14	10.5	0.5	0.2
34	38.3*	15	5.83	34.00	87.46	10.5	4.5	19.9
34	35*	6	5.83	34.00	34.99	10.5	-4.5	20.6
40	40*	13	6.32	40.00	82.22	11.4	1.6	2.5
40	36.9	16	6.32	40.00	101.19	11.4	4.6	20.9
42	34.4	20	6.48	42.00	129.61	11.7	8.3	68.6
42	30.8	16	6.48	42.00	103.69	11.7	4.3	18.4
43	39.4	12	6.56	43.00	78.69	11.9	0.1	0.0
43	39.4*	20	6.56	43.00	131.15	11.9	8.1	66.4
45	38.3	6	6.71	45.00	40.25	12.1	-6.1	37.5
45	38.3*	17	6.71	45.00	114.04	12.1	4.9	23.8
67	31.1	11	8.19	67.00	90.04	14.8	-3.8	14.4
42	33.3	12	6.48	42.00	77.77	11.7	0.3	0.1
42	33.3*	17	6.48	42.00	110.17	11.7	5.3	27.9
42	36.9	7	6.48	42.00	45.37	11.7	-4.7	22.2
42	36.9*	11	6.48	42.00	71.29	11.7	-0.7	0.5
16	32.2	7	4.00	16.00	28.00	7.2	-0.2	0.1
25	35.6*	4	5.00	25.00	20.00	9.0	-5.0	25.4
25	35.6	3	5.00	25.00	15.00	9.0	-6.0	36.5
44	30.8*	12	6.63	44.00	79.60	12.0	0.0	0.0
44	30.8	13	6.63	44.00	86.23	12.0	1.0	1.0
			Sum	**1165.00**	**2105.85**	**Mean**	**-0.2**	
						Std. Dev.	**4.2**	
						+2x(Std. Dev.)	**8.4**	
						-2x(Std. Dev.)	**-8.4**	

Note: * refers to assumed value

No. of Results: 33

k	1.81

Sum of Residual^2	559.5

BRIDGES IN CAPE PENINSULA LOCALITY

Grade 30 (Exposed Elements with Compressive Strengths: 31-40 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.6

$d_c = kt^{0.6}$

Age (t)	Strength	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\, t_i^{0.6}$	Predicted	Residual	Residual^2
33	39.4	8	8.15	66.41	65.19	10.3	-2.3	5.2
33	32.2	10	8.15	66.41	81.49	10.3	-0.3	0.1
33	32.2*	18	8.15	66.41	146.68	10.3	7.7	59.6
33	39.2*	5	8.15	66.41	40.75	10.3	-5.3	27.9
33	39.2	6	8.15	66.41	48.89	10.3	-4.3	18.3
33	39.2	9	8.15	66.41	73.34	10.3	-1.3	1.6
17	34*	4	5.47	29.96	21.89	6.9	-2.9	8.4
17	34	8	5.47	29.96	43.79	6.9	1.1	1.2
17	40*	4	5.47	29.96	21.89	6.9	-2.9	8.4
17	40*	4	5.47	29.96	21.89	6.9	-2.9	8.4
34	36.1	9	8.30	68.83	74.67	10.5	-1.5	2.2
34	36.1*	10	8.30	68.83	82.96	10.5	-0.5	0.2
34	38.3	11	8.30	68.83	91.26	10.5	0.5	0.3
34	38.3*	15	8.30	68.83	124.45	10.5	4.5	20.5
34	35*	6	8.30	68.83	49.78	10.5	-4.5	20.0
40	40*	13	9.15	83.65	118.90	11.5	1.5	2.1
40	36.9	16	9.15	83.65	146.34	11.5	4.5	19.9
42	34.4	20	9.42	88.70	188.36	11.9	8.1	65.9
42	30.8	16	9.42	88.70	150.68	11.9	4.1	17.0
43	39.4	12	9.55	91.24	114.62	12.1	-0.1	0.0
43	39.4*	20	9.55	91.24	191.03	12.1	7.9	63.2
45	38.3	6	9.82	96.35	58.90	12.4	-6.4	40.8
45	38.3*	17	9.82	96.35	166.87	12.4	4.6	21.3
67	31.1	11	12.46	155.34	137.10	15.7	-4.7	22.3
42	33.3	12	9.42	88.70	113.01	11.9	0.1	0.0
42	33.3*	17	9.42	88.70	160.10	11.9	5.1	26.2
42	36.9	7	9.42	88.70	65.92	11.9	-4.9	23.8
42	36.9*	11	9.42	88.70	103.60	11.9	-0.9	0.8
16	32.2	7	5.28	27.86	36.95	6.7	0.3	0.1
25	35.6*	4	6.90	47.59	27.59	8.7	-4.7	22.1
25	35.6	3	6.90	47.59	20.70	8.7	-5.7	32.5
44	30.8*	12	9.68	93.79	116.21	12.2	-0.2	0.0
44	30.8	13	9.68	93.79	125.90	12.2	0.8	0.6
			Sum	**2403.03**	**3031.71**	**Mean**	**-0.2**	
						Std. Dev.	**4.1**	
						+2x(Std. Dev.)	**8.2**	
						-2x(Std. Dev.)	**-8.2**	

Note: * refers to assumed value

No. of Results: 33

k	1.26

Sum of Residual^2	541.1

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.3**

$d_c = kt^{0.3}$

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\ t_i^{0.3}$	Predicted	Residual	Residual^2
15	49.4	7	2.25	5.08	15.77	7.9	-0.9	0.8
15	49.4*	7	2.25	5.08	15.77	7.9	-0.9	0.8
16	42.5	4	2.30	5.28	9.19	8.1	-4.1	16.5
17	46.38	8	2.34	5.47	18.72	8.2	-0.2	0.0
17	46.38*	7	2.34	5.47	16.38	8.2	-1.2	1.5
17	43.8*	5	2.34	5.47	11.70	8.2	-3.2	10.3
17	43.8	4	2.34	5.47	9.36	8.2	-4.2	17.7
17	43.3	9	2.34	5.47	21.06	8.2	0.8	0.6
17	43.3	10	2.34	5.47	23.40	8.2	1.8	3.2
20	44.4*	4	2.46	6.03	9.83	8.6	-4.6	21.4
20	44.4	5	2.46	6.03	12.28	8.6	-3.6	13.1
22	45*	8	2.53	6.39	20.22	8.9	-0.9	0.8
22	45	8	2.53	6.39	20.22	8.9	-0.9	0.8
22	41.6*	15	2.53	6.39	37.92	8.9	6.1	37.5
22	**41.6**	**18**	**2.53**	**6.39**	**45.50**	**8.9**	**9.1**	**83.3**
33	40.5	8	2.85	8.15	22.84	10.0	-2.0	4.1
33	40.5	9	2.85	8.15	25.69	10.0	-1.0	1.0
33	48.8	13	2.85	8.15	37.11	10.0	3.0	8.9
33	**48.8***	**19**	**2.85**	**8.15**	**54.24**	**10.0**	**9.0**	**80.6**
41	41.6	7	3.05	9.28	21.33	10.7	-3.7	13.6
			Sum	**127.78**	**448.51**	**Mean**	**-0.1**	
						Std. Dev.	**4.1**	
						+2x(Std. Dev.)	**8.2**	
						-2x(Std. Dev.)	**-8.2**	

Note: values in bold are outliers
 * refers to assumed value

No. of Results: 20

k	**3.51**

Sum of Residual^2	**316.7**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.3

$d_c = kt^{0.3}$

(After the 1st Elimination of Gross Outliers)

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\ t_i^{0.3}$	Predicted	Residual	Residual^2
15	49.4	7	2.25	5.08	15.77	6.9	0.1	0.0
15	49.4*	7	2.25	5.08	15.77	6.9	0.1	0.0
16	42.5	4	2.30	5.28	9.19	7.1	-3.1	9.5
17	46.38	8	2.34	5.47	18.72	7.2	0.8	0.6
17	46.38*	7	2.34	5.47	16.38	7.2	-0.2	0.0
17	43.8*	5	2.34	5.47	11.70	7.2	-2.2	4.9
17	43.8	4	2.34	5.47	9.36	7.2	-3.2	10.3
17	43.3	9	2.34	5.47	21.06	7.2	1.8	3.2
17	43.3	10	2.34	5.47	23.40	7.2	2.8	7.8
20	44.4*	4	2.46	6.03	9.83	7.6	-3.6	12.7
20	44.4	5	2.46	6.03	12.28	7.6	-2.6	6.6
22	45*	8	2.53	6.39	20.22	7.8	0.2	0.0
22	45	8	2.53	6.39	20.22	7.8	0.2	0.0
22	**41.6***	**15**	**2.53**	**6.39**	**37.92**	**7.8**	**7.2**	**52.1**
33	40.5	8	2.85	8.15	22.84	8.8	-0.8	0.6
33	40.5	9	2.85	8.15	25.69	8.8	0.2	0.0
33	48.8	13	2.85	8.15	37.11	8.8	4.2	17.7
41	41.6	7	3.05	9.28	21.33	9.4	-2.4	5.7
			Sum	**113.24**	**348.77**	**Mean**	**0.0**	
						Std. Dev.	**2.8**	
						+2x(Std. Dev.)	**5.6**	
						-2x(Std. Dev.)	**-5.6**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	3.08

Sum of Residual^2	131.8

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.3**

$d_c = kt^{0.3}$

(After the 2nd Elimination of Gross Outliers)

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\, t_i^{0.3}$	Predicted	Residual	Residual^2
15	49.4	7	2.25	5.08	15.77	6.6	0.4	0.2
15	49.4*	7	2.25	5.08	15.77	6.6	0.4	0.2
16	42.5	4	2.30	5.28	9.19	6.7	-2.7	7.2
17	46.38	8	2.34	5.47	18.72	6.8	1.2	1.4
17	46.38*	7	2.34	5.47	16.38	6.8	0.2	0.0
17	43.8*	5	2.34	5.47	11.70	6.8	-1.8	3.3
17	43.8	4	2.34	5.47	9.36	6.8	-2.8	7.9
17	43.3	9	2.34	5.47	21.06	6.8	2.2	4.8
17	43.3	10	2.34	5.47	23.40	6.8	3.2	10.2
20	44.4*	4	2.46	6.03	9.83	7.1	-3.1	9.9
20	44.4	5	2.46	6.03	12.28	7.1	-2.1	4.6
22	45*	8	2.53	6.39	20.22	7.4	0.6	0.4
22	45	8	2.53	6.39	20.22	7.4	0.6	0.4
33	40.5	8	2.85	8.15	22.84	8.3	-0.3	0.1
33	40.5	9	2.85	8.15	25.69	8.3	0.7	0.5
33	**48.8**	**13**	**2.85**	**8.15**	**37.11**	**8.3**	**4.7**	**22.0**
41	41.6	7	3.05	9.28	21.33	8.9	-1.9	3.5
			Sum	**106.85**	**310.86**	**Mean**	**0.0**	
						Std. Dev.	**2.2**	
						+2x(Std. Dev.)	**4.4**	
						-2x(Std. Dev.)	**-4.4**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	**2.91**

Sum of Residual^2	**76.6**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.3

$d_c = kt^{0.3}$

(After 3rd Elimination of Outliers)

Age (t)	Grade	d_c	$t^{0.3}$	$t^{0.6}$	$d_{ci}\ t_i^{0.3}$	Predicted	Residual	Residual^2
15	49.4	7	2.25	5.08	15.77	6.2	0.8	0.6
15	49.4*	7	2.25	5.08	15.77	6.2	0.8	0.6
16	42.5	4	2.30	5.28	9.19	6.4	-2.4	5.6
17	46.38	8	2.34	5.47	18.72	6.5	1.5	2.3
17	46.38*	7	2.34	5.47	16.38	6.5	0.5	0.3
17	43.8*	5	2.34	5.47	11.70	6.5	-1.5	2.2
17	43.8	4	2.34	5.47	9.36	6.5	-2.5	6.2
17	43.3	9	2.34	5.47	21.06	6.5	2.5	6.3
17	43.3	10	2.34	5.47	23.40	6.5	3.5	12.3
20	44.4*	4	2.46	6.03	9.83	6.8	-2.8	7.9
20	44.4	5	2.46	6.03	12.28	6.8	-1.8	3.3
22	45*	8	2.53	6.39	20.22	7.0	1.0	1.0
22	45	8	2.53	6.39	20.22	7.0	1.0	1.0
33	40.5	8	2.85	8.15	22.84	7.9	0.1	0.0
33	40.5	9	2.85	8.15	25.69	7.9	1.1	1.2
41	41.6	7	3.05	9.28	21.33	8.4	-1.4	2.1
			Sum	**98.70**	**273.75**	**Mean**	**0.0**	
						Std. Dev.	**1.9**	
						+2x(Std. Dev.)	**3.8**	
						-2x(Std. Dev.)	**-3.8**	

* refers to assumed value

No. of Results: 16

k	2.77

Sum of Residual^2	52.8

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.4**

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	7.6	-0.6	0.4
15	49.4*	7	2.95	8.73	20.68	7.6	-0.6	0.4
16	42.5	4	3.03	9.19	12.13	7.8	-3.8	14.4
17	46.38	8	3.11	9.65	24.85	8.0	0.0	0.0
17	46.38*	7	3.11	9.65	21.74	8.0	-1.0	1.0
17	43.8*	5	3.11	9.65	15.53	8.0	-3.0	8.9
17	43.8	4	3.11	9.65	12.42	8.0	-4.0	15.9
17	43.3	9	3.11	9.65	27.95	8.0	1.0	1.0
17	43.3	10	3.11	9.65	31.06	8.0	2.0	4.0
20	44.4*	4	3.31	10.99	13.26	8.5	-4.5	20.5
20	44.4	5	3.31	10.99	16.57	8.5	-3.5	12.4
22	45*	8	3.44	11.86	27.55	8.9	-0.9	0.7
22	45	8	3.44	11.86	27.55	8.9	-0.9	0.7
22	41.6*	15	3.44	11.86	51.65	8.9	6.1	37.7
22	**41.6**	**18**	**3.44**	**11.86**	**61.98**	**8.9**	**9.1**	**83.6**
33	40.5	8	4.05	16.40	32.40	10.4	-2.4	5.8
33	40.5	9	4.05	16.40	36.45	10.4	-1.4	2.0
33	48.8	13	4.05	16.40	52.64	10.4	2.6	6.7
33	**48.8***	**19**	**4.05**	**16.40**	**76.94**	**10.4**	**8.6**	**73.6**
41	41.6	7	4.42	19.51	30.92	11.4	-4.4	19.0
			Sum	**239.02**	**614.93**	**Mean**	**-0.1**	
						Std. Dev.	**4.0**	
						+2x(Std. Dev.)	**8.1**	
						-2x(Std. Dev.)	**-8.1**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 20

k	**2.57**

Sum of Residual^2	**309.0**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

(After the 1st Elimination of Gross Outliers)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.7	0.3	0.1
15	49.4*	7	2.95	8.73	20.68	6.7	0.3	0.1
16	42.5	4	3.03	9.19	12.13	6.8	-2.8	8.1
17	46.38	8	3.11	9.65	24.85	7.0	1.0	1.0
17	46.38*	7	3.11	9.65	21.74	7.0	0.0	0.0
17	43.8*	5	3.11	9.65	15.53	7.0	-2.0	4.1
17	43.8	4	3.11	9.65	12.42	7.0	-3.0	9.1
17	43.3	9	3.11	9.65	27.95	7.0	2.0	3.9
17	43.3	10	3.11	9.65	31.06	7.0	3.0	8.9
20	44.4*	4	3.31	10.99	13.26	7.5	-3.5	12.1
20	44.4	5	3.31	10.99	16.57	7.5	-2.5	6.2
22	45*	8	3.44	11.86	27.55	7.8	0.2	0.0
22	45	8	3.44	11.86	27.55	7.8	0.2	0.0
22	**41.6***	**15**	**3.44**	**11.86**	**51.65**	**7.8**	**7.2**	**52.2**
33	40.5	8	4.05	16.40	32.40	9.1	-1.1	1.3
33	40.5	9	4.05	16.40	36.45	9.1	-0.1	0.0
33	48.8	13	4.05	16.40	52.64	9.1	3.9	14.9
41	41.6	7	4.42	19.51	30.92	10.0	-3.0	8.9
			Sum	**210.77**	**476.01**	**Mean**	**0.0**	
						Std. Dev.	**2.8**	
						+2x(Std. Dev.)	**5.6**	
						-2x(Std. Dev.)	**-5.6**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	2.26

Sum of Residual^2	130.9

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.3	0.7	0.5
15	49.4*	7	2.95	8.73	20.68	6.3	0.7	0.5
16	42.5	4	3.03	9.19	12.13	6.5	-2.5	6.1
17	46.38	8	3.11	9.65	24.85	6.6	1.4	1.9
17	46.38*	7	3.11	9.65	21.74	6.6	0.4	0.1
17	43.8*	5	3.11	9.65	15.53	6.6	-1.6	2.6
17	43.8	4	3.11	9.65	12.42	6.6	-2.6	6.9
17	43.3	9	3.11	9.65	27.95	6.6	2.4	5.6
17	43.3	10	3.11	9.65	31.06	6.6	3.4	11.4
20	44.4*	4	3.31	10.99	13.26	7.1	-3.1	9.4
20	44.4	5	3.31	10.99	16.57	7.1	-2.1	4.3
22	45*	8	3.44	11.86	27.55	7.3	0.7	0.4
22	45	8	3.44	11.86	27.55	7.3	0.7	0.4
33	40.5	8	4.05	16.40	32.40	8.6	-0.6	0.4
33	40.5	9	4.05	16.40	36.45	8.6	0.4	0.1
33	**48.8**	**13**	**4.05**	**16.40**	**52.64**	**8.6**	**4.4**	**19.0**
41	41.6	7	4.42	19.51	30.92	9.4	-2.4	5.9
			Sum	**198.91**	**424.36**	**Mean**	**0.0**	
						Std. Dev.	**2.2**	
						+2x(Std. Dev.)	**4.3**	
						-2x(Std. Dev.)	**-4.3**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 17

k	2.13

Sum of Residual^2	75.6

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

(After the 3rd Dlimination of Gross Outliers)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.0	1.0	1.0
15	49.4*	7	2.95	8.73	20.68	6.0	1.0	1.0
16	42.5	4	3.03	9.19	12.13	6.2	-2.2	4.7
17	46.38	8	3.11	9.65	24.85	6.3	1.7	2.8
17	46.38*	7	3.11	9.65	21.74	6.3	0.7	0.5
17	43.8*	5	3.11	9.65	15.53	6.3	-1.3	1.8
17	43.8	4	3.11	9.65	12.42	6.3	-2.3	5.4
17	43.3	9	3.11	9.65	27.95	6.3	2.7	7.2
17	43.3	10	3.11	9.65	31.06	6.3	3.7	13.5
20	44.4*	4	3.31	10.99	13.26	6.8	-2.8	7.6
20	44.4	5	3.31	10.99	16.57	6.8	-1.8	3.1
22	45*	8	3.44	11.86	27.55	7.0	1.0	1.0
22	45	8	3.44	11.86	27.55	7.0	1.0	1.0
33	40.5	8	4.05	16.40	32.40	8.2	-0.2	0.1
33	40.5	9	4.05	16.40	36.45	8.2	0.8	0.6
41	41.6	7	4.42	19.51	30.92	9.0	-2.0	4.0
			Sum	**182.51**	**371.72**	**Mean**	**0.1**	
						Std. Dev.	**1.9**	
						+2x(Std. Dev.)	**3.8**	
						-2x(Std. Dev.)	**-3.8**	

* refers to assumed value

No. of Results: 16

k	2.04

Sum of Residual^2	54.9

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.5**

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
15	49.4	7	3.87	15.00	27.11	7.3	-0.3	0.1
15	49.4*	7	3.87	15.00	27.11	7.3	-0.3	0.1
16	42.5	4	4.00	16.00	16.00	7.5	-3.5	12.4
17	46.38	8	4.12	17.00	32.98	7.7	0.3	0.1
17	46.38*	7	4.12	17.00	28.86	7.7	-0.7	0.6
17	43.8*	5	4.12	17.00	20.62	7.7	-2.7	7.6
17	43.8	4	4.12	17.00	16.49	7.7	-3.7	14.1
17	43.3	9	4.12	17.00	37.11	7.7	1.3	1.6
17	43.3	10	4.12	17.00	41.23	7.7	2.3	5.1
20	44.4*	4	4.47	20.00	17.89	8.4	-4.4	19.4
20	44.4	5	4.47	20.00	22.36	8.4	-3.4	11.6
22	45*	8	4.69	22.00	37.52	8.8	-0.8	0.7
22	45	8	4.69	22.00	37.52	8.8	-0.8	0.7
22	41.6*	15	4.69	22.00	70.36	8.8	6.2	38.2
22	**41.6**	**18**	4.69	22.00	**84.43**	8.8	**9.2**	**84.4**
33	40.5	8	5.74	33.00	45.96	10.8	-2.8	7.8
33	40.5	9	5.74	33.00	51.70	10.8	-1.8	3.2
33	48.8	13	5.74	33.00	74.68	10.8	2.2	4.9
33	**48.8***	**19**	5.74	33.00	**109.15**	10.8	**8.2**	**67.3**
41	41.6	7	6.40	41.00	44.82	12.0	-5.0	25.3
			Sum	**449.00**	**843.90**	**Mean**	**0.0**	
						Std. Dev.	**4.0**	
						+2x(Std. Dev.)	**8.0**	
						-2x(Std. Dev.)	**-8.0**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 20

k	**1.88**

Sum of Residual^2	**304.9**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.5**

$d_c = kt^{0.5}$

(After 1st Elimination of Outliers)

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
15	49.4	7	3.87	15.00	27.11	6.4	0.6	0.4
15	49.4*	7	3.87	15.00	27.11	6.4	0.6	0.4
16	42.5	4	4.00	16.00	16.00	6.6	-2.6	6.8
17	46.38	8	4.12	17.00	32.98	6.8	1.2	1.4
17	46.38*	7	4.12	17.00	28.86	6.8	0.2	0.0
17	43.8*	5	4.12	17.00	20.62	6.8	-1.8	3.3
17	43.8	4	4.12	17.00	16.49	6.8	-2.8	7.9
17	43.3	9	4.12	17.00	37.11	6.8	2.2	4.8
17	43.3	10	4.12	17.00	41.23	6.8	3.2	10.2
20	44.4*	4	4.47	20.00	17.89	7.4	-3.4	11.4
20	44.4	5	4.47	20.00	22.36	7.4	-2.4	5.7
22	45*	8	4.69	22.00	37.52	7.7	0.3	0.1
22	45	8	4.69	22.00	37.52	7.7	0.3	0.1
22	**41.6***	**15**	**4.69**	**22.00**	**70.36**	**7.7**	**7.3**	**52.7**
33	40.5	8	5.74	33.00	45.96	9.5	-1.5	2.2
33	40.5	9	5.74	33.00	51.70	9.5	-0.5	0.2
33	48.8	13	5.74	33.00	74.68	9.5	3.5	12.4
41	41.6	7	6.40	41.00	44.82	10.6	-3.6	12.7
			Sum	**394.00**	**650.33**	**Mean**	**0.0**	
						Std. Dev.	**2.8**	
						+2x(Std. Dev.)	**5.6**	
						-2x(Std. Dev.)	**-5.6**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	**1.65**

Sum of Residual^2	**132.6**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

(After 2nd Elimination of Outliers)

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	$Residual^2$
15	49.4	7	3.87	15.00	27.11	6.0	1.0	0.9
15	49.4*	7	3.87	15.00	27.11	6.0	1.0	0.9
16	42.5	4	4.00	16.00	16.00	6.2	-2.2	5.0
17	46.38	8	4.12	17.00	32.98	6.4	1.6	2.5
17	46.38*	7	4.12	17.00	28.86	6.4	0.6	0.3
17	43.8*	5	4.12	17.00	20.62	6.4	-1.4	2.0
17	43.8	4	4.12	17.00	16.49	6.4	-2.4	5.9
17	43.3	9	4.12	17.00	37.11	6.4	2.6	6.6
17	43.3	10	4.12	17.00	41.23	6.4	3.6	12.8
20	44.4*	4	4.47	20.00	17.89	7.0	-3.0	8.8
20	44.4	5	4.47	20.00	22.36	7.0	-2.0	3.9
22	45*	8	4.69	22.00	37.52	7.3	0.7	0.5
22	45	8	4.69	22.00	37.52	7.3	0.7	0.5
33	40.5	8	5.74	33.00	45.96	9.0	-1.0	0.9
33	40.5	9	5.74	33.00	51.70	9.0	0.0	0.0
33	48.8	13	5.74	33.00	74.68	9.0	4.0	16.4
41	41.6	7	6.40	41.00	44.82	10.0	-3.0	8.9
			Sum	**372.00**	**579.97**	**Mean**	**0.0**	
						Std. Dev.	**2.2**	
						+2x(Std. Dev.)	**4.4**	
						-2x(Std. Dev.)	**-4.4**	

* refers to assumed value

No. of Results: 17

k	1.56

Sum of $Residual^2$	76.8

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares

n	**0.6**

$d_c = kt^{0.6}$

Age (t)	Grade	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\, t_i^{0.6}$	Predicted	Residual	Residual^2
15	49.4	7	5.08	25.78	35.54	6.9	0.1	0.0
15	49.4*	7	5.08	25.78	35.54	6.9	0.1	0.0
16	42.5	4	5.28	27.86	21.11	7.2	-3.2	10.4
17	46.38	8	5.47	29.96	43.79	7.5	0.5	0.3
17	46.38*	7	5.47	29.96	38.31	7.5	-0.5	0.2
17	43.8*	5	5.47	29.96	27.37	7.5	-2.5	6.2
17	43.8	4	5.47	29.96	21.89	7.5	-3.5	12.2
17	43.3	9	5.47	29.96	49.26	7.5	1.5	2.3
17	43.3	10	5.47	29.96	54.74	7.5	2.5	6.3
20	44.4*	4	6.03	36.41	24.14	8.3	-4.3	18.1
20	44.4	5	6.03	36.41	30.17	8.3	-3.3	10.6
22	45*	8	6.39	40.82	51.11	8.7	-0.7	0.6
22	45	8	6.39	40.82	51.11	8.7	-0.7	0.6
22	41.6*	15	6.39	40.82	95.84	8.7	6.3	39.1
22	**41.6**	**18**	6.39	40.82	**115.01**	8.7	**9.3**	**85.7**
33	40.5	8	8.15	66.41	65.19	11.2	-3.2	9.9
33	40.5	9	8.15	66.41	73.34	11.2	-2.2	4.6
33	48.8	13	8.15	66.41	105.94	11.2	1.8	3.4
33	48.8*	19	8.15	66.41	154.83	11.2	7.8	61.6
41	41.6	7	9.28	86.17	64.98	12.7	-5.7	32.5
			Sum	**847.09**	**1159.23**	**Mean**	**0.0**	
						Std. Dev.	**4.0**	
						+2x(Std. Dev.)	**8.0**	
						-2x(Std. Dev.)	**-8.0**	

Note: values in bold are outliers

* refers to assumed value

No. of Results: 20

k	**1.37**

Sum of Residual^2	**304.6**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Outliers)

n	**0.6**

$d_c = kt^{0.6}$

Age (t)	Grade	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\, t_i^{0.6}$	Predicted	Residual	Residual^2
15	49.4	7	5.08	25.78	35.54	6.6	0.4	0.2
15	49.4*	7	5.08	25.78	35.54	6.6	0.4	0.2
16	42.5	4	5.28	27.86	21.11	6.8	-2.8	8.0
17	46.38	8	5.47	29.96	43.79	7.1	0.9	0.8
17	46.38*	7	5.47	29.96	38.31	7.1	-0.1	0.0
17	43.8*	5	5.47	29.96	27.37	7.1	-2.1	4.4
17	43.8	4	5.47	29.96	21.89	7.1	-3.1	9.5
17	43.3	9	5.47	29.96	49.26	7.1	1.9	3.7
17	43.3	10	5.47	29.96	54.74	7.1	2.9	8.5
20	44.4*	4	6.03	36.41	24.14	7.8	-3.8	14.6
20	44.4	5	6.03	36.41	30.17	7.8	-2.8	7.9
22	45*	8	6.39	40.82	51.11	8.3	-0.3	0.1
22	45	8	6.39	40.82	51.11	8.3	-0.3	0.1
22	41.6*	15	6.39	40.82	95.84	8.3	6.7	45.2
33	40.5	8	8.15	66.41	65.19	10.6	-2.6	6.5
33	40.5	9	8.15	66.41	73.34	10.6	-1.6	2.4
33	48.8	13	8.15	66.41	105.94	10.6	2.4	6.0
33	**48.8***	**19**	**8.15**	**66.41**	**154.83**	**10.6**	**8.4**	**71.3**
41	41.6	7	9.28	86.17	64.98	12.0	-5.0	25.2
			Sum	**806.27**	**1044.22**	**Mean**	**0.0**	
						Std. Dev.	**3.5**	
						+2x(Std. Dev.)	**6.9**	
						-2x(Std. Dev.)	**-6.9**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 19

k	**1.30**

Sum of Residual^2	**214.6**

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Outliers)

n	0.6

$d_c = kt^{0.6}$

Age (t)	Grade	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\ t_i^{0.6}$	Predicted	Residual	Residual^2
15	49.4	7	5.08	25.78	35.54	6.1	0.9	0.8
15	49.4*	7	5.08	25.78	35.54	6.1	0.9	0.8
16	42.5	4	5.28	27.86	21.11	6.3	-2.3	5.5
17	46.38	8	5.47	29.96	43.79	6.6	1.4	2.0
17	46.38*	7	5.47	29.96	38.31	6.6	0.4	0.2
17	43.8*	5	5.47	29.96	27.37	6.6	-1.6	2.5
17	43.8	4	5.47	29.96	21.89	6.6	-2.6	6.7
17	43.3	9	5.47	29.96	49.26	6.6	2.4	5.9
17	43.3	10	5.47	29.96	54.74	6.6	3.4	11.7
20	44.4*	4	6.03	36.41	24.14	7.3	-3.3	10.6
20	44.4	5	6.03	36.41	30.17	7.3	-2.3	5.1
22	45*	8	6.39	40.82	51.11	7.7	0.3	0.1
22	45	8	6.39	40.82	51.11	7.7	0.3	0.1
22	**41.6***	**15**	**6.39**	**40.82**	**95.84**	**7.7**	**7.3**	**53.6**
33	40.5	8	8.15	66.41	65.19	9.8	-1.8	3.2
33	40.5	9	8.15	66.41	73.34	9.8	-0.8	0.6
33	48.8	13	8.15	66.41	105.94	9.8	3.2	10.3
41	41.6	7	9.28	86.17	64.98	11.2	-4.2	17.3
			Sum	**739.86**	**889.39**	**Mean**	**0.1**	
						Std. Dev.	**2.8**	
						+2x(Std. Dev.)	**5.7**	
						-2x(Std. Dev.)	**-5.7**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 18

k	1.20

Sum of Residual^2	136.9

BRIDGES OF CAPE PENINSULA

Grade 40 (Exposed Elements with Compressive Strengths: 41-50 MPa at 28 days)

Method of Analysis: Method of Least Squares
(After the 3rd Elimination of Outliers)

n	**0.6**

$d_c = kt^{0.6}$

Age (t)	Grade	d_c	$t^{0.6}$	$t^{1.2}$	$d_{ci}\ t_i^{0.6}$	Predicted	Residual	Residual^2
15	49.4	7	5.08	25.78	35.54	5.8	1.2	1.5
15	49.4*	7	5.08	25.78	35.54	5.8	1.2	1.5
16	42.5	4	5.28	27.86	21.11	6.0	-2.0	4.0
17	46.38	8	5.47	29.96	43.79	6.2	1.8	3.2
17	46.38*	7	5.47	29.96	38.31	6.2	0.8	0.6
17	43.8*	5	5.47	29.96	27.37	6.2	-1.2	1.5
17	43.8	4	5.47	29.96	21.89	6.2	-2.2	4.9
17	43.3	9	5.47	29.96	49.26	6.2	2.8	7.8
17	43.3	10	5.47	29.96	54.74	6.2	3.8	14.3
20	44.4*	4	6.03	36.41	24.14	6.8	-2.8	8.1
20	44.4	5	6.03	36.41	30.17	6.8	-1.8	3.4
22	45*	8	6.39	40.82	51.11	7.3	0.7	0.6
22	45	8	6.39	40.82	51.11	7.3	0.7	0.6
33	40.5	8	8.15	66.41	65.19	9.3	-1.3	1.6
33	40.5	9	8.15	66.41	73.34	9.3	-0.3	0.1
33	48.8	13	8.15	66.41	105.94	9.3	3.7	14.1
41	41.6	7	9.28	86.17	64.98	10.5	-3.5	12.5
			Sum	**699.04**	**793.55**	**Mean**	**0.1**	
						Std. Dev.	**2.2**	
						+2x(Std. Dev.)	**4.5**	
						-2x(Std. Dev.)	**-4.5**	

* refers to assumed value

No. of Results: 17

k	**1.14**

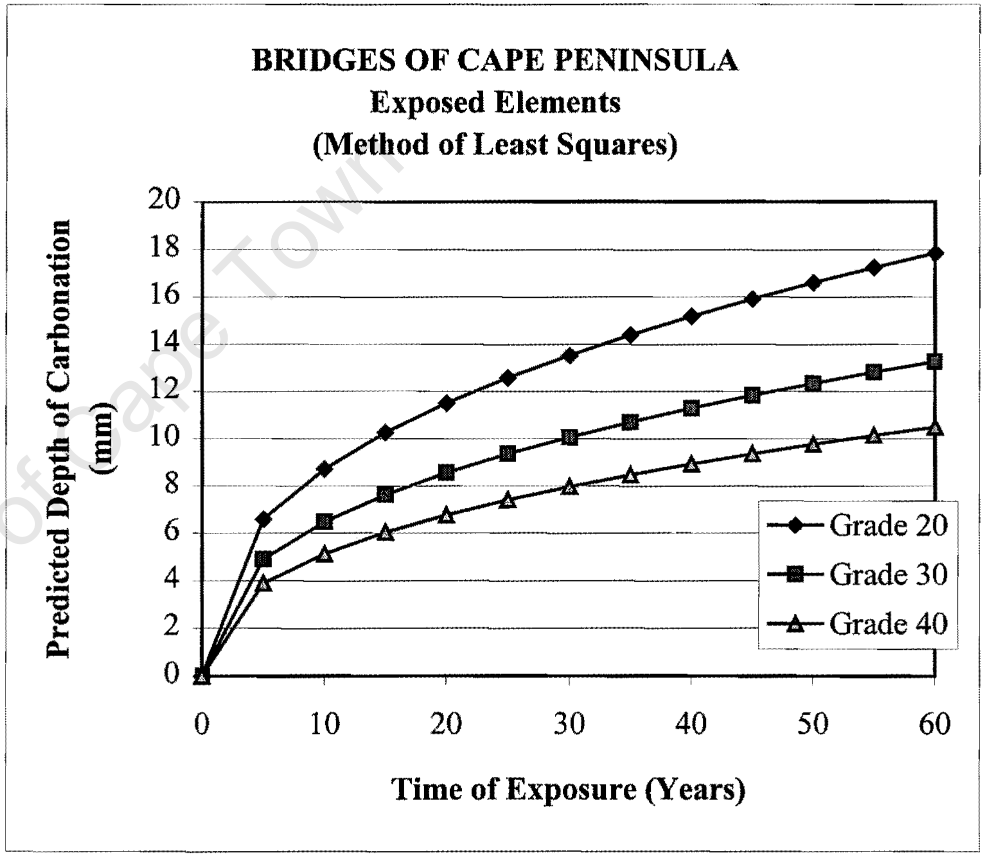
Sum of Residual^2	**80.2**

BRIDGES IN CAPE PENINSULA

Comparison of Carbonation Prediction Models

Method of Analysis: Method of Least Squares

Time	Depth of Carbonation, d_c, (mm)		
(t)	Grade 20	Grade 30	Grade 40
(Years)	$d_c = 3.47t^{0.4}$	$d_c = 2.58t^{0.4}$	$d_c = 2.04t^{0.4}$
0	0.0	0.0	0.0
5	6.6	4.9	3.9
10	8.7	6.5	5.1
15	10.3	7.6	6.0
20	11.5	8.6	6.8
25	12.6	9.3	7.4
30	13.5	10.1	8.0
35	14.4	10.7	8.5
40	15.2	11.3	8.9
45	15.9	11.8	9.4
50	16.6	12.3	9.8
55	17.2	12.8	10.1
60	17.8	13.3	10.5



APPENDIX E

ANALYSIS OF DURBAN LOCALITY DATA USING THE METHOD OF LEAST SQUARES

(Data were provided by Mr. Graham Moore)

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Exposed Elements Between 1970-1982)
Method of Analysis: Method of Least Squares

n	0.4		$d_c = kt^{0.4}$					
Age (t)	**Grade**	**d_c**	**$t^{0.4}$**	**$t^{0.8}$**	**$d_{ci}\ t_i^{0.4}$**	**Predicted**	**Residual**	**Residual^2**
19	25	27	3.25	10.54	87.67	15.7	11.3	127.6
19	25	18	3.25	10.54	58.45	15.7	2.3	5.3
21	20	17	3.38	11.42	57.46	16.3	0.7	0.4
21	25	26	3.38	11.42	87.87	16.3	9.7	93.2
24	25	25	3.57	12.71	89.13	17.2	7.8	60.2
24	25	26	3.57	12.71	92.70	17.2	8.8	76.7
25	25	18	3.62	13.13	65.23	17.5	0.5	0.2
25	25	21	3.62	13.13	76.10	17.5	3.5	12.1
25	25	22	3.62	13.13	79.73	17.5	4.5	20.0
25	25	23	3.62	13.13	83.35	17.5	5.5	30.0
25	25	14	3.62	13.13	50.73	17.5	-3.5	12.4
25	25	20	3.62	13.13	72.48	17.5	2.5	6.1
25	25	12	3.62	13.13	43.49	17.5	-5.5	30.5
25	25	16	3.62	13.13	57.98	17.5	-1.5	2.3
25	25	22	3.62	13.13	79.73	17.5	4.5	20.0
26	25	16	3.68	13.55	58.90	17.8	-1.8	3.3
26	25	12	3.68	13.55	44.17	17.8	-5.8	33.7
28	25	12	3.79	14.38	45.50	18.3	-6.3	40.2
28	25	15	3.79	14.38	56.88	18.3	-3.3	11.2
29	20	12	3.85	14.79	46.15	18.6	-6.6	43.5
29	25	11	3.85	14.79	42.30	18.6	-7.6	57.7
29	20	12	3.85	14.79	46.15	18.6	-6.6	43.5
29	20	23	3.85	14.79	88.45	18.6	4.4	19.4
29	25	16	3.85	14.79	61.53	18.6	-2.6	6.8
29	20	19	3.85	14.79	73.07	18.6	0.4	0.2
23	25	25	3.51	12.29	87.63	17.0	8.0	64.8
23	25	22	3.51	12.29	77.11	17.0	5.0	25.5
23	25	23	3.51	12.29	80.62	17.0	6.0	36.6
23	25	20	3.51	12.29	70.10	17.0	3.0	9.3
23	25	15	3.51	12.29	52.58	17.0	-2.0	3.8
23	25	24	3.51	12.29	84.12	17.0	7.0	49.7
23	25	19	3.51	12.29	66.60	17.0	2.0	4.2
23	25	22	3.51	12.29	77.11	17.0	5.0	25.5
23	25	24	3.51	12.29	84.12	17.0	7.0	49.7
23	25	18	3.51	12.29	63.09	17.0	1.0	1.1
23	25	8	3.51	12.29	28.04	17.0	-9.0	80.1
23	25	10	3.51	12.29	35.05	17.0	-7.0	48.3
24	25	9	3.57	12.71	32.09	17.2	-8.2	67.9
24	25	10	3.57	12.71	35.65	17.2	-7.2	52.5
30	25	12	3.90	15.19	46.78	18.9	-6.9	47.0
30	**25**	**6**	**3.90**	**15.19**	**23.39**	**18.9**	**-12.9**	165.2
			Sum	**535.37**	**2589.24**	**Mean**	**0.2**	
						Std. Dev	**6.1**	
						+2x(Std. Dev	**12.2**	
						-2x(Std. Dev)	**-12.2**	

Note: values in bold are outliers

No. of Results: 41

k	**4.84**
Sum of Residual^2	**1487.5**

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Exposed Elements Between 1970-1982)
Method of Analysis: Method of Least Squares
(After the 1st Elimination of Outliers)

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	**d_c**	**$t^{0.4}$**	**$t^{0.8}$**	**$d_{ci}\, t_i^{0.4}$**	**Predicted**	**Residual**	**Residual^2**
19	25	27	3.25	10.54	87.67	16.0	11.0	120.6
19	25	18	3.25	10.54	58.45	16.0	2.0	3.9
21	20	17	3.38	11.42	57.46	16.7	0.3	0.1
21	25	26	3.38	11.42	87.87	16.7	9.3	87.0
24	25	25	3.57	12.71	89.13	17.6	7.4	55.0
24	25	26	3.57	12.71	92.70	17.6	8.4	70.8
25	25	18	3.62	13.13	65.23	17.9	0.1	0.0
25	25	21	3.62	13.13	76.10	17.9	3.1	9.8
25	25	22	3.62	13.13	79.73	17.9	4.1	17.0
25	25	23	3.62	13.13	83.35	17.9	5.1	26.3
25	25	14	3.62	13.13	50.73	17.9	-3.9	15.0
25	25	20	3.62	13.13	72.48	17.9	2.1	4.5
25	25	12	3.62	13.13	43.49	17.9	-5.9	34.5
25	25	16	3.62	13.13	57.98	17.9	-1.9	3.5
25	25	22	3.62	13.13	79.73	17.9	4.1	17.0
26	25	16	3.68	13.55	58.90	18.2	-2.2	4.7
26	25	12	3.68	13.55	44.17	18.2	-6.2	37.9
28	25	12	3.79	14.38	45.50	18.7	-6.7	44.9
28	25	15	3.79	14.38	56.88	18.7	-3.7	13.7
29	20	12	3.85	14.79	46.15	19.0	-7.0	48.6
29	25	11	3.85	14.79	42.30	19.0	-8.0	63.5
29	20	12	3.85	14.79	46.15	19.0	-7.0	48.6
29	20	23	3.85	14.79	88.45	19.0	4.0	16.3
29	25	16	3.85	14.79	61.53	19.0	-3.0	8.8
29	20	19	3.85	14.79	73.07	19.0	0.0	0.0
23	25	25	3.51	12.29	87.63	17.3	7.7	59.5
23	25	22	3.51	12.29	77.11	17.3	4.7	22.2
23	25	23	3.51	12.29	80.62	17.3	5.7	32.6
23	25	20	3.51	12.29	70.10	17.3	2.7	7.3
23	25	15	3.51	12.29	52.58	17.3	-2.3	5.2
23	25	24	3.51	12.29	84.12	17.3	6.7	45.0
23	25	19	3.51	12.29	66.60	17.3	1.7	2.9
23	25	22	3.51	12.29	77.11	17.3	4.7	22.2
23	25	24	3.51	12.29	84.12	17.3	6.7	45.0
23	25	18	3.51	12.29	63.09	17.3	0.7	0.5
23	25	8	3.51	12.29	28.04	17.3	-9.3	86.3
23	25	10	3.51	12.29	35.05	17.3	-7.3	53.1
24	25	9	3.57	12.71	32.09	17.6	-8.6	73.7
24	25	10	3.57	12.71	35.65	17.6	-7.6	57.5
30	25	12	3.90	15.19	46.78	19.2	-7.2	52.2
			Sum	**520.18**	**2565.86**	**Mean**	**0.1**	
						Std. Dev	**5.8**	
						+2x(Std. Dev	**11.6**	
						-2x(Std. Dev)	**-11.6**	

No. of Results: 40

k	4.93

Sum of Residual^2	1317.5

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Exposed Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	**0.5**	$d_c = kt^{0.5}$						
Age (t)	**Grade**	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	**Predicted**	**Residual**	**Residual²**
19	25	27	4.36	19.00	117.69	15.2	11.8	138.1
19	25	18	4.36	19.00	78.46	15.2	2.8	7.6
21	20	17	4.58	21.00	77.90	16.0	1.0	0.9
21	25	26	4.58	21.00	119.15	16.0	10.0	99.4
24	25	25	4.90	24.00	122.47	17.1	7.9	61.9
24	25	26	4.90	24.00	127.37	17.1	8.9	78.6
25	25	18	5.00	25.00	90.00	17.5	0.5	0.3
25	25	21	5.00	25.00	105.00	17.5	3.5	12.3
25	25	22	5.00	25.00	110.00	17.5	4.5	20.4
25	25	23	5.00	25.00	115.00	17.5	5.5	30.4
25	25	14	5.00	25.00	70.00	17.5	-3.5	12.2
25	25	20	5.00	25.00	100.00	17.5	2.5	6.3
25	25	12	5.00	25.00	60.00	17.5	-5.5	30.1
25	25	16	5.00	25.00	80.00	17.5	-1.5	2.2
25	25	22	5.00	25.00	110.00	17.5	4.5	20.4
26	25	16	5.10	26.00	81.58	17.8	-1.8	3.4
26	25	12	5.10	26.00	61.19	17.8	-5.8	34.0
28	25	12	5.29	28.00	63.50	18.5	-6.5	42.4
28	25	15	5.29	28.00	79.37	18.5	-3.5	12.3
29	20	12	5.39	29.00	64.62	18.8	-6.8	46.7
29	25	11	5.39	29.00	59.24	18.8	-7.8	61.4
29	20	12	5.39	29.00	64.62	18.8	-6.8	46.7
29	20	23	5.39	29.00	123.86	18.8	4.2	17.3
29	25	16	5.39	29.00	86.16	18.8	-2.8	8.0
29	20	19	5.39	29.00	102.32	18.8	0.2	0.0
23	25	25	4.80	23.00	119.90	16.8	8.2	67.7
23	25	22	4.80	23.00	105.51	16.8	5.2	27.3
23	25	23	4.80	23.00	110.30	16.8	6.2	38.8
23	25	20	4.80	23.00	95.92	16.8	3.2	10.4
23	25	15	4.80	23.00	71.94	16.8	-1.8	3.1
23	25	24	4.80	23.00	115.10	16.8	7.2	52.2
23	25	19	4.80	23.00	91.12	16.8	2.2	5.0
23	25	22	4.80	23.00	105.51	16.8	5.2	27.3
23	25	24	4.80	23.00	115.10	16.8	7.2	52.2
23	25	18	4.80	23.00	86.32	16.8	1.2	1.5
23	25	8	4.80	23.00	38.37	16.8	-8.8	77.0
23	25	10	4.80	23.00	47.96	16.8	-6.8	45.9
24	25	9	4.90	24.00	44.09	17.1	-8.1	66.2
24	25	10	4.90	24.00	48.99	17.1	-7.1	50.9
30	25	12	5.48	30.00	65.73	19.2	-7.2	51.2
30	**25**	**6**	5.48	30.00	**32.86**	19.2	**-13.2**	173.1
			Sum	**1019.00**	**3564.22**	**Mean**	**0.2**	
						Std. Dev	**6.2**	
						+2x(Std. Dev	**12.4**	
						-2x(Std. Dev)	**-12.4**	

Note: values in bold are outliers

No. of Results: 41

k	**3.50**
Sum of Residual²	**1543.2**

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Exposed Elements Between 1970-1982)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Outliers)

n	0.5	$d_c = kt^{0.5}$						
Age (t)	**Grade**	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	**Predicted**	**Residual**	**Residual²**
19	25	27	4.36	19.00	117.69	15.6	11.4	130.8
19	25	18	4.36	19.00	78.46	15.6	2.4	5.9
21	20	17	4.58	21.00	77.90	16.4	0.6	0.4
21	25	26	4.58	21.00	119.15	16.4	9.6	92.9
24	25	25	4.90	24.00	122.47	17.5	7.5	56.4
24	25	26	4.90	24.00	127.37	17.5	8.5	72.4
25	25	18	5.00	25.00	90.00	17.9	0.1	0.0
25	25	21	5.00	25.00	105.00	17.9	3.1	9.9
25	25	22	5.00	25.00	110.00	17.9	4.1	17.2
25	25	23	5.00	25.00	115.00	17.9	5.1	26.5
25	25	14	5.00	25.00	70.00	17.9	-3.9	14.8
25	25	20	5.00	25.00	100.00	17.9	2.1	4.6
25	25	12	5.00	25.00	60.00	17.9	-5.9	34.3
25	25	16	5.00	25.00	80.00	17.9	-1.9	3.4
25	25	22	5.00	25.00	110.00	17.9	4.1	17.2
26	25	16	5.10	26.00	81.58	18.2	-2.2	4.9
26	25	12	5.10	26.00	61.19	18.2	-6.2	38.5
28	25	12	5.29	28.00	63.50	18.9	-6.9	47.5
28	25	15	5.29	28.00	79.37	18.9	-3.9	15.2
29	20	12	5.39	29.00	64.62	19.2	-7.2	52.3
29	25	11	5.39	29.00	59.24	19.2	-8.2	67.7
29	20	12	5.39	29.00	64.62	19.2	-7.2	52.3
29	20	23	5.39	29.00	123.86	19.2	3.8	14.2
29	25	16	5.39	29.00	86.16	19.2	-3.2	10.4
29	20	19	5.39	29.00	102.32	19.2	-0.2	0.1
23	25	25	4.80	23.00	119.90	17.1	7.9	62.0
23	25	22	4.80	23.00	105.51	17.1	4.9	23.8
23	25	23	4.80	23.00	110.30	17.1	5.9	34.5
23	25	20	4.80	23.00	95.92	17.1	2.9	8.3
23	25	15	4.80	23.00	71.94	17.1	-2.1	4.5
23	25	24	4.80	23.00	115.10	17.1	6.9	47.3
23	25	19	4.80	23.00	91.12	17.1	1.9	3.5
23	25	22	4.80	23.00	105.51	17.1	4.9	23.8
23	25	24	4.80	23.00	115.10	17.1	6.9	47.3
23	25	18	4.80	23.00	86.32	17.1	0.9	0.8
23	25	8	4.80	23.00	38.37	17.1	-9.1	83.3
23	25	10	4.80	23.00	47.96	17.1	-7.1	50.8
24	25	9	4.90	24.00	44.09	17.5	-8.5	72.1
24	25	10	4.90	24.00	48.99	17.5	-7.5	56.1
30	25	12	5.48	30.00	65.73	19.6	-7.6	57.1
			Sum	**989.00**	**3531.36**	**Mean**	**0.2**	
						Std. Dev	**5.9**	
						+2x(Std. Dev	**11.8**	
						-2x(Std. Dev)	**-11.8**	

No. of Results: 40

k	3.57

Sum of Residual²	1364.8

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares

n	**0.4**

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
37	20	9	4.24	17.97	38.15	12.0	-3.0	8.7
37	20	13	4.24	17.97	55.11	12.0	1.0	1.1
38	20	18	4.28	18.36	77.12	12.1	5.9	35.0
38	20	12	4.28	18.36	51.42	12.1	-0.1	0.0
38	20	7	4.28	18.36	29.99	12.1	-5.1	25.9
44	20	14	4.54	20.64	63.61	12.8	1.2	1.4
44	20	20	4.54	20.64	90.87	12.8	7.2	51.6
45	20	9	4.58	21.02	41.26	12.9	-3.9	15.4
45	20	14	4.58	21.02	64.18	12.9	1.1	1.1
45	20	8	4.58	21.02	36.68	12.9	-4.9	24.3
40	20	16	4.37	19.13	69.98	12.3	3.7	13.4
40	20	20	4.37	19.13	87.47	12.3	7.7	58.7
40	20	16	4.37	19.13	69.98	12.3	3.7	13.4
45	**20**	**0**	**4.58**	**21.02**	**0.00**	**12.9**	**-12.9**	**167.2**
45	20	12	4.58	21.02	55.01	12.9	-0.9	0.9
45	20	2	4.58	21.02	9.17	12.9	-10.9	119.5
45	20	10	4.58	21.02	45.84	12.9	-2.9	8.6
44	20	10	4.54	20.64	45.43	12.8	-2.8	7.9
44	20	19	4.54	20.64	86.32	12.8	6.2	38.3
44	20	14	4.54	20.64	63.61	12.8	1.2	1.4
44	20	12	4.54	20.64	54.52	12.8	-0.8	0.7
44	20	15	4.54	20.64	68.15	12.8	2.2	4.8
44	20	21	4.54	20.64	95.41	12.8	8.2	67.0
			Sum	**460.66**	**1299.28**	**Mean**	**0.0**	
						Std. Dev	**5.5**	
						+2x(Std. Dev	**11.0**	
						-2x(Std. Dev)	**-11.0**	

Note: values in bold are outliers

No. of Results: 23

k	**2.82**

Sum of Residual^2	**666.4**

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	Predicted	Residual	Residual^2
37	20	9	4.24	17.97	38.15	12.0	-3.0	8.7
37	20	13	4.24	17.97	55.11	12.0	1.0	1.1
38	20	18	4.28	18.36	77.12	12.1	5.9	35.0
38	20	12	4.28	18.36	51.42	12.1	-0.1	0.0
38	20	7	4.28	18.36	29.99	12.1	-5.1	25.9
44	20	14	4.54	20.64	63.61	12.8	1.2	1.4
44	20	20	4.54	20.64	90.87	12.8	7.2	51.6
45	20	9	4.58	21.02	41.26	12.9	-3.9	15.4
45	20	14	4.58	21.02	64.18	12.9	1.1	1.1
45	20	8	4.58	21.02	36.68	12.9	-4.9	24.3
40	20	16	4.37	19.13	69.98	12.3	3.7	13.4
40	20	20	4.37	19.13	87.47	12.3	7.7	58.7
40	20	16	4.37	19.13	69.98	12.3	3.7	13.4
45	20	12	4.58	21.02	55.01	12.9	-0.9	0.9
45	**20**	**2**	**4.58**	**21.02**	**9.17**	**12.9**	**-10.9**	**119.5**
45	20	10	4.58	21.02	45.84	12.9	-2.9	8.6
44	20	10	4.54	20.64	45.43	12.8	-2.8	7.9
44	20	19	4.54	20.64	86.32	12.8	6.2	38.3
44	20	14	4.54	20.64	63.61	12.8	1.2	1.4
44	20	12	4.54	20.64	54.52	12.8	-0.8	0.7
44	20	15	4.54	20.64	68.15	12.8	2.2	4.8
44	20	21	4.54	20.64	95.41	12.8	8.2	67.0
			Sum	**439.64**	**1299.28**	**Mean**	**0.6**	
						Std. Dev	**4.8**	
						+2x(Std. Dev)	**9.7**	
						-2x(Std. Dev)	**-9.7**	

Note: values in bold are outliers

No. of Results: 22

k	2.96

Sum of Residual^2	499.2

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
37	20	9	4.24	17.97	38.15	13.1	-4.1	16.5
37	20	13	4.24	17.97	55.11	13.1	-0.1	0.0
38	20	18	4.28	18.36	77.12	13.2	4.8	23.0
38	20	12	4.28	18.36	51.42	13.2	-1.2	1.5
38	20	7	4.28	18.36	29.99	13.2	-6.2	38.5
44	20	14	4.54	20.64	63.61	14.0	0.0	0.0
44	20	20	4.54	20.64	90.87	14.0	6.0	36.0
45	20	9	4.58	21.02	41.26	14.1	-5.1	26.3
45	20	14	4.58	21.02	64.18	14.1	-0.1	0.0
45	20	8	4.58	21.02	36.68	14.1	-6.1	37.6
40	20	16	4.37	19.13	69.98	13.5	2.5	6.4
40	20	20	4.37	19.13	87.47	13.5	6.5	42.5
40	20	16	4.37	19.13	69.98	13.5	2.5	6.4
45	20	12	4.58	21.02	55.01	14.1	-2.1	4.5
45	20	10	4.58	21.02	45.84	14.1	-4.1	17.0
44	20	10	4.54	20.64	45.43	14.0	-4.0	16.0
44	20	19	4.54	20.64	86.32	14.0	5.0	25.0
44	20	14	4.54	20.64	63.61	14.0	0.0	0.0
44	20	12	4.54	20.64	54.52	14.0	-2.0	4.0
44	20	15	4.54	20.64	68.15	14.0	1.0	1.0
44	20	21	4.54	20.64	95.41	14.0	7.0	49.0
			Sum	**418.62**	**1290.11**	**Mean**	**0.0**	
						Std. Dev	**4.2**	
						+2x(Std. Dev	**8.4**	
						-2x(Std. Dev)	**-8.4**	

Note: values in bold are outliers

No. of Results: 21

k	**3.08**

Sum of Residual^2	**351.1**

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
37	20	9	6.08	37.00	54.74	11.8	-2.8	7.8
37	20	13	6.08	37.00	79.08	11.8	1.2	1.5
38	20	18	6.16	38.00	110.96	11.9	6.1	36.7
38	20	12	6.16	38.00	73.97	11.9	0.1	0.0
38	20	7	6.16	38.00	43.15	11.9	-4.9	24.4
44	20	14	6.63	44.00	92.87	12.9	1.1	1.3
44	20	20	6.63	44.00	132.66	12.9	7.1	51.1
45	20	9	6.71	45.00	60.37	13.0	-4.0	16.0
45	20	14	6.71	45.00	93.91	13.0	1.0	1.0
45	20	8	6.71	45.00	53.67	13.0	-5.0	25.0
40	20	16	6.32	40.00	101.19	12.3	3.7	14.0
40	20	20	6.32	40.00	126.49	12.3	7.7	60.0
40	20	16	6.32	40.00	101.19	12.3	3.7	14.0
45	**20**	**0**	6.71	45.00	**0.00**	13.0	**-13.0**	168.9
45	20	12	6.71	45.00	80.50	13.0	-1.0	1.0
45	20	2	6.71	45.00	13.42	13.0	-11.0	120.9
45	20	10	6.71	45.00	67.08	13.0	-3.0	9.0
44	20	10	6.63	44.00	66.33	12.9	-2.9	8.1
44	20	19	6.63	44.00	126.03	12.9	6.1	37.8
44	20	14	6.63	44.00	92.87	12.9	1.1	1.3
44	20	12	6.63	44.00	79.60	12.9	-0.9	0.7
44	20	15	6.63	44.00	99.50	12.9	2.1	4.6
44	20	21	6.63	44.00	139.30	12.9	8.1	66.4
			Sum	**975.00**	**1888.89**	**Mean**	**0.0**	
						Std. Dev	**5.5**	
						+2x(Std. Dev	**11.1**	
						-2x(Std. Dev)	**-11.1**	

Note: values in bold are outliers

No. of Results: 23

k	1.94

Sum of Residual^2	671.6

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	**0.5**

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\,t_i^{0.5}$	Predicted	Residual	Residual^2
37	20	9	6.08	37.00	54.74	12.4	-3.4	11.3
37	20	13	6.08	37.00	79.08	12.4	0.6	0.4
38	20	18	6.16	38.00	110.96	12.5	5.5	30.0
38	20	12	6.16	38.00	73.97	12.5	-0.5	0.3
38	20	7	6.16	38.00	43.15	12.5	-5.5	30.5
44	20	14	6.63	44.00	92.87	13.5	0.5	0.3
44	20	20	6.63	44.00	132.66	13.5	6.5	42.6
45	20	9	6.71	45.00	60.37	13.6	-4.6	21.4
45	20	14	6.71	45.00	93.91	13.6	0.4	0.1
45	20	8	6.71	45.00	53.67	13.6	-5.6	31.6
40	20	16	6.32	40.00	101.19	12.8	3.2	10.0
40	20	20	6.32	40.00	126.49	12.8	7.2	51.2
40	20	16	6.32	40.00	101.19	12.8	3.2	10.0
45	20	12	6.71	45.00	80.50	13.6	-1.6	2.6
45	**20**	**2**	**6.71**	**45.00**	**13.42**	**13.6**	**-11.6**	**135.1**
45	20	10	6.71	45.00	67.08	13.6	-3.6	13.1
44	20	10	6.63	44.00	66.33	13.5	-3.5	12.1
44	20	19	6.63	44.00	126.03	13.5	5.5	30.6
44	20	14	6.63	44.00	92.87	13.5	0.5	0.3
44	20	12	6.63	44.00	79.60	13.5	-1.5	2.2
44	20	15	6.63	44.00	99.50	13.5	1.5	2.3
44	20	21	6.63	44.00	139.30	13.5	7.5	56.7
			Sum	**930.00**	**1888.89**	**Mean**	**0.0**	
						Std. Dev	**4.9**	
						+2x(Std. Dev)	**9.7**	
						-2x(Std. Dev)	**-9.7**	

Note: values in bold are outliers

No. of Results: 22

k	**2.03**

Sum of Residual^2	**494.5**

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Exposed Elements Between 1956-1964)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	**0.5**

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
37	20	9	6.08	37.00	54.74	12.9	-3.9	15.1
37	20	13	6.08	37.00	79.08	12.9	0.1	0.0
38	20	18	6.16	38.00	110.96	13.1	4.9	24.4
38	20	12	6.16	38.00	73.97	13.1	-1.1	1.1
38	20	7	6.16	38.00	43.15	13.1	-6.1	36.8
44	20	14	6.63	44.00	92.87	14.1	-0.1	0.0
44	20	20	6.63	44.00	132.66	14.1	5.9	35.3
45	20	9	6.71	45.00	60.37	14.2	-5.2	27.2
45	20	14	6.71	45.00	93.91	14.2	-0.2	0.0
45	20	8	6.71	45.00	53.67	14.2	-6.2	38.6
40	20	16	6.32	40.00	101.19	13.4	2.6	6.7
40	20	20	6.32	40.00	126.49	13.4	6.6	43.5
40	20	16	6.32	40.00	101.19	13.4	2.6	6.7
45	20	12	6.71	45.00	80.50	14.2	-2.2	4.9
45	20	10	6.71	45.00	67.08	14.2	-4.2	17.8
44	20	10	6.63	44.00	66.33	14.1	-4.1	16.5
44	20	19	6.63	44.00	126.03	14.1	4.9	24.4
44	20	14	6.63	44.00	92.87	14.1	-0.1	0.0
44	20	12	6.63	44.00	79.60	14.1	-2.1	4.2
44	20	15	6.63	44.00	99.50	14.1	0.9	0.9
44	20	21	6.63	44.00	139.30	14.1	6.9	48.2
			Sum	**885.00**	**1875.47**	**Mean**	**0.0**	
						Std. Dev	**4.2**	
						+2x(Std. Dev	**8.4**	
						-2x(Std. Dev)	**-8.4**	

Note: values in bold are outliers

No. of Results: 21

k	**2.12**

Sum of Residual^2	**352.5**

BRIDGES IN DURBAN LOCALITY

Grade 30-35 (Exposed Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
21	30	10	3.38	11.42	33.80	12.7	-2.7	7.2
25	30	5	3.62	13.13	18.12	13.6	-8.6	73.8
25	30	12	3.62	13.13	43.49	13.6	-1.6	2.5
25	30	13	3.62	13.13	47.11	13.6	-0.6	0.3
26	30	16	3.68	13.55	58.90	13.8	2.2	4.8
28	30	21	3.79	14.38	79.63	14.2	6.8	46.0
28	30	18	3.79	14.38	68.26	14.2	3.8	14.3
28	30	15	3.79	14.38	56.88	14.2	0.8	0.6
28	30	22	3.79	14.38	83.42	14.2	7.8	60.5
17	35	12	3.11	9.65	37.27	11.6	0.4	0.1
17	30	20	3.11	9.65	62.12	11.6	8.4	69.8
17	30	2	3.11	9.65	6.21	11.6	-9.6	93.1
17	35	12	3.11	9.65	37.27	11.6	0.4	0.1
17	30	14	3.11	9.65	43.48	11.6	2.4	5.5
17	30	7	3.11	9.65	21.74	11.6	-4.6	21.6
23	30	13	3.51	12.29	45.57	13.1	-0.1	0.0
23	30	22	3.51	12.29	77.11	13.1	8.9	78.4
23	30	14	3.51	12.29	49.07	13.1	0.9	0.7
23	30	2	3.51	12.29	7.01	13.1	-11.1	124.2
30	30	10	3.90	15.19	38.98	14.6	-4.6	21.3
			Sum	**244.10**	**915.43**	**Mean**	**-0.1**	
						Std. Dev	**5.7**	
						+2x(Std. Dev	**11.5**	
						-2x(Std. Dev)	**-11.5**	

No. of Results: 20

k	3.75

Sum of Residual^2	624.9

BRIDGES IN DURBAN LOCALITY

Grade 30-35 (Exposed Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
21	30	10	4.58	21.00	45.83	12.6	-2.6	6.5
25	30	5	5.00	25.00	25.00	13.7	-8.7	75.7
25	30	12	5.00	25.00	60.00	13.7	-1.7	2.9
25	30	13	5.00	25.00	65.00	13.7	-0.7	0.5
26	30	16	5.10	26.00	81.58	14.0	2.0	4.1
28	30	21	5.29	28.00	111.12	14.5	6.5	42.2
28	30	18	5.29	28.00	95.25	14.5	3.5	12.2
28	30	15	5.29	28.00	79.37	14.5	0.5	0.2
28	30	22	5.29	28.00	116.41	14.5	7.5	56.2
17	35	12	4.12	17.00	49.48	11.3	0.7	0.5
17	30	20	4.12	17.00	82.46	11.3	8.7	75.7
17	30	2	4.12	17.00	8.25	11.3	-9.3	86.5
17	35	12	4.12	17.00	49.48	11.3	0.7	0.5
17	30	14	4.12	17.00	57.72	11.3	2.7	7.3
17	30	7	4.12	17.00	28.86	11.3	-4.3	18.5
23	30	13	4.80	23.00	62.35	13.1	-0.1	0.0
23	30	22	4.80	23.00	105.51	13.1	8.9	78.4
23	30	14	4.80	23.00	67.14	13.1	0.9	0.7
23	30	2	4.80	23.00	9.59	13.1	-11.1	124.2
30	30	10	5.48	30.00	54.77	15.0	-5.0	25.1
			Sum	**458.00**	**1255.17**	**Mean**	**-0.1**	
						Std. Dev	**5.7**	
						+2x(Std. Dev	**11.4**	
						-2x(Std. Dev)	**-11.4**	

No. of Results: 20

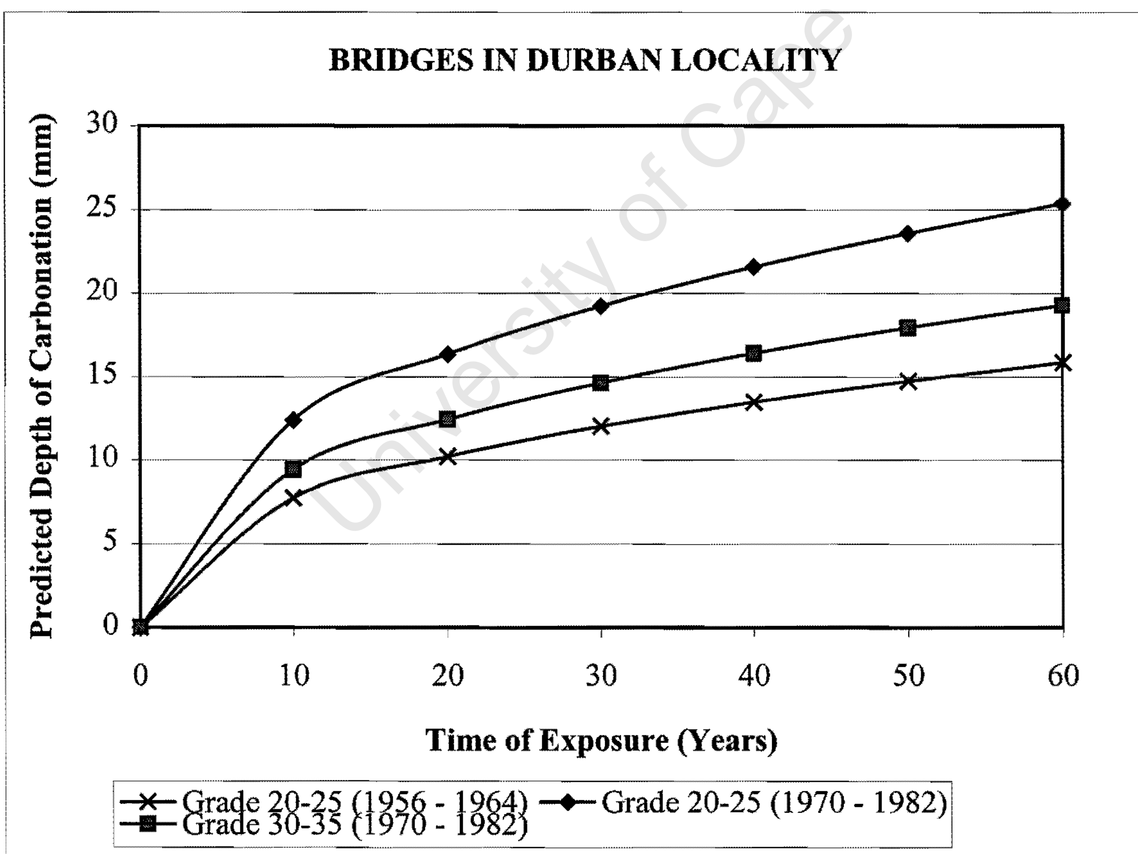
k	2.74

Sum of Residual^2	618.1

BRIDGES IN DURBAN LOCALITY

Comparison Between Exposed Grade 20-25 and 30-35

	Predicted carbonation depth, d_c (mm)		
Time	**Grade 20-25**	**Grade 20-25**	**Grade 30-35**
(t)	**(1956 - 1964)**	**(1970 - 1982)**	**(1970 - 1982)**
(Years)	$d_c = 3.08t^{0.4}$	$d_c = 4.93t^{0.4}$	$d_c = 3.75t^{0.4}$
0	0.0	0.0	0.0
10	7.7	12.4	9.4
20	10.2	16.3	12.4
30	12.0	19.2	14.6
40	13.5	21.6	16.4
50	14.7	23.6	17.9
60	15.8	25.4	19.3



BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Sheltered Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
19	25	17	3.25	10.54	55.20	15.7	1.3	1.8
21	25	21	3.38	11.42	70.98	16.3	4.7	22.2
24	25	18	3.57	12.71	64.17	17.2	0.8	0.7
24	25	24	3.57	12.71	85.56	17.2	6.8	46.5
25	25	24	3.62	13.13	86.97	17.5	6.5	42.7
25	25	19	3.62	13.13	68.85	17.5	1.5	2.3
25	25	22	3.62	13.13	79.73	17.5	4.5	20.5
25	25	28	3.62	13.13	101.47	17.5	10.5	110.9
25	25	21	3.62	13.13	76.10	17.5	3.5	12.5
25	25	24	3.62	13.13	86.97	17.5	6.5	42.7
26	25	20	3.68	13.55	73.62	17.7	2.3	5.1
28	25	13	3.79	14.38	49.30	18.3	-5.3	27.8
29	25	11	3.85	14.79	42.30	18.5	-7.5	56.8
29	20	10	3.85	14.79	38.46	18.5	-8.5	72.9
29	25	12	3.85	14.79	46.15	18.5	-6.5	42.7
29	20	15	3.85	14.79	57.68	18.5	-3.5	12.5
23	25	23	3.51	12.29	80.62	16.9	6.1	37.3
23	25	17	3.51	12.29	59.59	16.9	0.1	0.0
23	25	20	3.51	12.29	70.10	16.9	3.1	9.6
23	25	12	3.51	12.29	42.06	16.9	-4.9	24.0
24	25	21	3.57	12.71	74.87	17.2	3.8	14.6
24	25	5	3.57	12.71	17.83	17.2	-12.2	148.5
30	25	8	3.90	15.19	31.18	18.8	-10.8	116.4
30	25	19	3.90	15.19	74.06	18.8	0.2	0.0
			Sum	**318.22**	**1533.82**	**Mean**	**0.1**	
						Std. Dev	**6.2**	
						+2x(Std. Dev	**12.3**	
						-2x(Std. Dev)	**-12.3**	

No. of Results: 24

k	4.82

Sum of Residual^2	870.9

BRIDGES IN DURBAN LOCALITY

Grade 20-25 (Sheltered Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
19	25	17	4.36	19.00	74.10	15.2	1.8	3.4
21	25	21	4.58	21.00	96.23	15.9	5.1	25.5
24	25	18	4.90	24.00	88.18	17.0	1.0	0.9
24	25	24	4.90	24.00	117.58	17.0	7.0	48.3
25	25	24	5.00	25.00	120.00	17.4	6.6	43.6
25	25	19	5.00	25.00	95.00	17.4	1.6	2.6
25	25	22	5.00	25.00	110.00	17.4	4.6	21.2
25	25	28	5.00	25.00	140.00	17.4	10.6	112.3
25	25	21	5.00	25.00	105.00	17.4	3.6	13.0
25	25	24	5.00	25.00	120.00	17.4	6.6	43.6
26	25	20	5.10	26.00	101.98	17.7	2.3	5.1
28	25	13	5.29	28.00	68.79	18.4	-5.4	29.3
29	25	11	5.39	29.00	59.24	18.7	-7.7	59.9
29	20	10	5.39	29.00	53.85	18.7	-8.7	76.4
29	25	12	5.39	29.00	64.62	18.7	-6.7	45.4
29	20	15	5.39	29.00	80.78	18.7	-3.7	14.0
23	25	23	4.80	23.00	110.30	16.7	6.3	39.8
23	25	17	4.80	23.00	81.53	16.7	0.3	0.1
23	25	20	4.80	23.00	95.92	16.7	3.3	11.0
23	25	12	4.80	23.00	57.55	16.7	-4.7	22.0
24	25	21	4.90	24.00	102.88	17.0	4.0	15.6
24	25	5	4.90	24.00	24.49	17.0	-12.0	145.2
30	25	8	5.48	30.00	43.82	19.1	-11.1	122.4
30	25	19	5.48	30.00	104.07	19.1	-0.1	0.0
			Sum	**608.00**	**2115.91**	**Mean**	**0.2**	
						Std. Dev	**6.3**	
						+2x(Std. Dev	**12.5**	
						-2x(Std. Dev)	**-12.5**	

No. of Results: 24

k	3.48

Sum of Residual^2	900.4

BRIDGES IN DURBAN LOCALITY

Grade 30-35 (Sheltered Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
19	30	16	3.25	10.54	51.95	0.0	16.0	256.0
21	30	18	3.38	11.42	60.84	0.0	18.0	324.0
25	30	11	3.62	13.13	39.86	0.0	11.0	121.0
28	30	15	3.79	14.38	56.88	0.0	15.0	225.0
28	30	17	3.79	14.38	64.46	0.0	17.0	289.0
17	30	7	3.11	9.65	21.74	0.0	7.0	49.0
17	30	13	3.11	9.65	40.38	0.0	13.0	169.0
23	30	7	3.51	12.29	24.54	0.0	7.0	49.0
23	30	3	3.51	12.29	10.52	0.0	3.0	9.0
23	30	12	3.51	12.29	42.06	0.0	12.0	144.0
23	30	12	3.51	12.29	42.06	0.0	12.0	144.0
			Sum	**132.29**	**455.28**	**Mean**	**11.9**	
						Std. Dev	**4.7**	
						+2x(Std. Dev	**9.4**	
						-2x(Std. Dev)	**-9.4**	

No. of Results: 11

k	**3.44**
Sum of Residual^2	**1779.0**

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
19	30	16	1.00	1.00	16.00	0.0	16.0	256.0
21	30	18	1.00	1.00	18.00	0.0	18.0	324.0
25	30	11	1.00	1.00	11.00	0.0	11.0	121.0
28	30	15	1.00	1.00	15.00	0.0	15.0	225.0
28	30	17	1.00	1.00	17.00	0.0	17.0	289.0
17	30	7	1.00	1.00	7.00	0.0	7.0	49.0
17	30	13	1.00	1.00	13.00	0.0	13.0	169.0
23	30	7	1.00	1.00	7.00	0.0	7.0	49.0
23	30	3	1.00	1.00	3.00	0.0	3.0	9.0
23	30	12	1.00	1.00	12.00	0.0	12.0	144.0
23	30	12	1.00	1.00	12.00	0.0	12.0	144.0
			Sum	**11.00**	**131.00**	**Mean**	**11.9**	
						Std. Dev	**4.7**	
						+2x(Std. Dev	**9.4**	
						-2x(Std. Dev)	**-9.4**	

No. of Results: 11

k	**11.91**
Sum of Residual^2	**1779.0**

BRIDGES IN DURBAN LOCALITY

Grade 40-45 (Sheltered Elements Between 1970-1982)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
25	40	7	3.62	13.13	25.37	0.0	7.0	49.0
25	40	18	3.62	13.13	65.23	0.0	18.0	324.0
25	40	15	3.62	13.13	54.36	0.0	15.0	225.0
26	40	3	3.68	13.55	11.04	0.0	3.0	9.0
28	40	7	3.79	14.38	26.54	0.0	7.0	49.0
17	45	11	3.11	9.65	34.16	0.0	11.0	121.0
17	45	4	3.11	9.65	12.42	0.0	4.0	16.0
23	40	10	3.51	12.29	35.05	0.0	10.0	100.0
23	40	13	3.51	12.29	45.57	0.0	13.0	169.0
23	40	6	3.51	12.29	21.03	0.0	6.0	36.0
23	40	8	3.51	12.29	28.04	0.0	8.0	64.0
			Sum	135.76	358.82	Mean	9.3	
						Std. Dev	4.6	
						+2x(Std. Dev	9.3	
						-2x(Std. Dev)	-9.3	

No. of Results: 11

k	2.64
Sum of Residual^2	1162.0

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
25	40	7	1.00	1.00	7.00	0.0	7.0	49.0
25	40	18	1.00	1.00	18.00	0.0	18.0	324.0
25	40	15	1.00	1.00	15.00	0.0	15.0	225.0
26	40	3	1.00	1.00	3.00	0.0	3.0	9.0
28	40	7	1.00	1.00	7.00	0.0	7.0	49.0
17	45	11	1.00	1.00	11.00	0.0	11.0	121.0
17	45	4	1.00	1.00	4.00	0.0	4.0	16.0
23	40	10	1.00	1.00	10.00	0.0	10.0	100.0
23	40	13	1.00	1.00	13.00	0.0	13.0	169.0
23	40	6	1.00	1.00	6.00	0.0	6.0	36.0
23	40	8	1.00	1.00	8.00	0.0	8.0	64.0
			Sum	11.00	102.00	Mean	9.3	
						Std. Dev	4.6	
						+2x(Std. Dev	9.3	
						-2x(Std. Dev)	-9.3	

No. of Results: 11

k	9.27
Sum of Residual^2	1162.0

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Sheltered Elements Between 1956-1964)
Method of Analysis: Method of Least Squares

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	**Predicted**	**Residual**	**Residual^2**
37	20*	18	4.24	17.97	76.31	13.0	5.0	25.2
38	20	12	4.28	18.36	51.42	13.1	-1.1	1.2
38	20	14	4.28	18.36	59.98	13.1	0.9	0.8
44	20	9	4.54	20.64	40.89	13.9	-4.9	24.1
44	20	8	4.54	20.64	36.35	13.9	-5.9	34.9
45	20	14	4.58	21.02	64.18	14.0	0.0	0.0
45	20	5	4.58	21.02	22.92	14.0	-9.0	81.6
40	20	17	4.37	19.13	74.35	13.4	3.6	13.1
40	20	11	4.37	19.13	48.11	13.4	-2.4	5.7
45	20*	11	4.58	21.02	50.43	14.0	-3.0	9.2
45	20*	18	4.58	21.02	82.52	14.0	4.0	15.7
44	20*	17	4.54	20.64	77.24	13.9	3.1	9.6
44	**20**	**24**	**4.54**	**20.64**	**109.04**	**13.9**	**10.1**	101.9
44	20*	14	4.54	20.64	63.61	13.9	0.1	0.0
44	20	14	4.54	20.64	63.61	13.9	0.1	0.0
			Sum	**300.86**	**920.95**	**Mean**	**0.0**	
						Std. Dev	**4.8**	
						+2x(Std. Dev	**9.6**	
						-2x(Std. Dev)	**-9.6**	
					k	**3.06**		
					Sum of Residual^2		**323.0**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 15

(After the 1st Elimination of Gross Outliers)

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	**Predicted**	**Residual**	**Residual^2**
37	20*	18	4.24	17.97	76.31	12.3	5.7	32.7
38	20	12	4.28	18.36	51.42	12.4	-0.4	0.2
38	20	14	4.28	18.36	59.98	12.4	1.6	2.5
44	20	9	4.54	20.64	40.89	13.2	-4.2	17.3
44	20	8	4.54	20.64	36.35	13.2	-5.2	26.7
45	20	14	4.58	21.02	64.18	13.3	0.7	0.5
45	**20**	**5**	**4.58**	**21.02**	**22.92**	**13.3**	**-8.3**	**68.6**
40	20	17	4.37	19.13	74.35	12.7	4.3	18.7
40	20	11	4.37	19.13	48.11	12.7	-1.7	2.8
45	20*	11	4.58	21.02	50.43	13.3	-2.3	5.2
45	20*	18	4.58	21.02	82.52	13.3	4.7	22.3
44	20*	17	4.54	20.64	77.24	13.2	3.8	14.7
44	20*	14	4.54	20.64	63.61	13.2	0.8	0.7
44	20	14	4.54	20.64	63.61	13.2	0.8	0.7
			Sum	**280.22**	**811.91**	**Mean**	**0.0**	
						Std. Dev	**4.1**	
						+2x(Std. Dev	**8.1**	
						-2x(Std. Dev)	**-8.1**	
					k	**2.90**		
					Sum of Residual^2		**213.6**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 14

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Sheltered Elements Between 1956-1964)
Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	**Predicted**	**Residual**	**Residual^2**
37	20*	18	4.24	17.97	76.31	12.9	5.1	26.0
38	20	12	4.28	18.36	51.42	13.0	-1.0	1.1
38	20	14	4.28	18.36	59.98	13.0	1.0	0.9
44	20	9	4.54	20.64	40.89	13.8	-4.8	23.3
44	20	8	4.54	20.64	36.35	13.8	-5.8	34.0
45	20	14	4.58	21.02	64.18	14.0	0.0	0.0
40	20	17	4.37	19.13	74.35	13.3	3.7	13.6
40	20	11	4.37	19.13	48.11	13.3	-2.3	5.3
45	20*	11	4.58	21.02	50.43	14.0	-3.0	8.7
45	20*	18	4.58	21.02	82.52	14.0	4.0	16.4
44	20*	17	4.54	20.64	77.24	13.8	3.2	10.1
44	20*	14	4.54	20.64	63.61	13.8	0.2	0.0
44	20	14	4.54	20.64	63.61	13.8	0.2	0.0
			Sum	**259.20**	**788.98**	**Mean**	**0.0**	
						Std. Dev	**3.4**	
						+2x(Std. Dev	**6.8**	
						-2x(Std. Dev)	**-6.8**	
					k	**3.04**		
					Sum of Residual^2		**139.4**	

* refers to assumed value

No. of Results: 13

n	0.5	$d_c = kt^{0.5}$						
Age (t)	**Grade**	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	**Predicted**	**Residual**	**Residual^2**
37	20*	18	6.08	37.00	109.49	12.8	5.2	27.2
38	20	12	6.16	38.00	73.97	13.0	-1.0	0.9
38	20	14	6.16	38.00	86.30	13.0	1.0	1.1
44	20	9	6.63	44.00	59.70	13.9	-4.9	24.5
44	20	8	6.63	44.00	53.07	13.9	-5.9	35.4
45	20	14	6.71	45.00	93.91	14.1	-0.1	0.0
45	20	5	6.71	45.00	33.54	14.1	-9.1	82.9
40	20	17	6.32	40.00	107.52	13.3	3.7	13.7
40	20	11	6.32	40.00	69.57	13.3	-2.3	5.3
45	20*	11	6.71	45.00	73.79	14.1	-3.1	9.6
45	20*	18	6.71	45.00	120.75	14.1	3.9	15.2
44	20*	17	6.63	44.00	112.77	13.9	3.1	9.3
44	**20**	**24**	6.63	44.00	**159.20**	13.9	**10.1**	101.1
44	20*	14	6.63	44.00	92.87	13.9	0.1	0.0
44	20	14	6.63	44.00	92.87	13.9	0.1	0.0
			Sum	**637.00**	**1339.31**	**Mean**	**0.0**	
						Std. Dev	**4.8**	
						+2x(Std. Dev	**9.7**	
						-2x(Std. Dev)	**-9.7**	
					k	**2.10**		
					Sum of Residual^2		**326.1**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 15

BRIDGES IN DURBAN LOCALITY
Grade 20-25 (Sheltered Elements Between 1956-1964)
Method of Analysis: Method of Least Squares

(After the 1st Elimination of Gross Outliers)

n	0.5	$d_c = kt^{0.5}$						
Age (t)	**Grade**	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	**Predicted**	**Residual**	**Residual²**
37	20*	18	6.08	37.00	109.49	12.1	5.9	34.8
38	20	12	6.16	38.00	73.97	12.3	-0.3	0.1
38	20	14	6.16	38.00	86.30	12.3	1.7	3.0
44	20	9	6.63	44.00	59.70	13.2	-4.2	17.6
44	20	8	6.63	44.00	53.07	13.2	-5.2	27.0
45	20	14	6.71	45.00	93.91	13.3	0.7	0.4
45	**20**	**5**	**6.71**	**45.00**	**33.54**	13.3	**-8.3**	**69.7**
40	20	17	6.32	40.00	107.52	12.6	4.4	19.5
40	20	11	6.32	40.00	69.57	12.6	-1.6	2.5
45	20*	11	6.71	45.00	73.79	13.3	-2.3	5.5
45	20*	18	6.71	45.00	120.75	13.3	4.7	21.6
44	20*	17	6.63	44.00	112.77	13.2	3.8	14.4
44	20*	14	6.63	44.00	92.87	13.2	0.8	0.6
44	20	14	6.63	44.00	92.87	13.2	0.8	0.6
			Sum	**593.00**	**1180.11**	**Mean**	**0.1**	
						Std. Dev	**4.1**	
						+2x(Std. Dev	**8.2**	
						-2x(Std. Dev)	**-8.2**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 14

k	**1.99**
Sum of Residual²	**217.5**

(After the 2nd Elimination of Gross Outliers)

n	0.5	$d_c = kt^{0.5}$						
Age (t)	**Grade**	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	**Predicted**	**Residual**	**Residual²**
37	20*	18	6.08	37.00	109.49	12.7	5.3	27.8
38	20	12	6.16	38.00	73.97	12.9	-0.9	0.8
38	20	14	6.16	38.00	86.30	12.9	1.1	1.2
44	20	9	6.63	44.00	59.70	13.9	-4.9	23.8
44	20	8	6.63	44.00	53.07	13.9	-5.9	34.6
45	20	14	6.71	45.00	93.91	14.0	0.0	0.0
40	20	17	6.32	40.00	107.52	13.2	3.8	14.2
40	20	11	6.32	40.00	69.57	13.2	-2.2	5.0
45	20*	11	6.71	45.00	73.79	14.0	-3.0	9.2
45	20*	18	6.71	45.00	120.75	14.0	4.0	15.7
44	20*	17	6.63	44.00	112.77	13.9	3.1	9.7
44	20*	14	6.63	44.00	92.87	13.9	0.1	0.0
44	20	14	6.63	44.00	92.87	13.9	0.1	0.0
			Sum	**548.00**	**1146.57**	**Mean**	**0.0**	
						Std. Dev	**3.4**	
						+2x(Std. Dev	**6.9**	
						-2x(Std. Dev)	**-6.9**	

* refers to assumed value

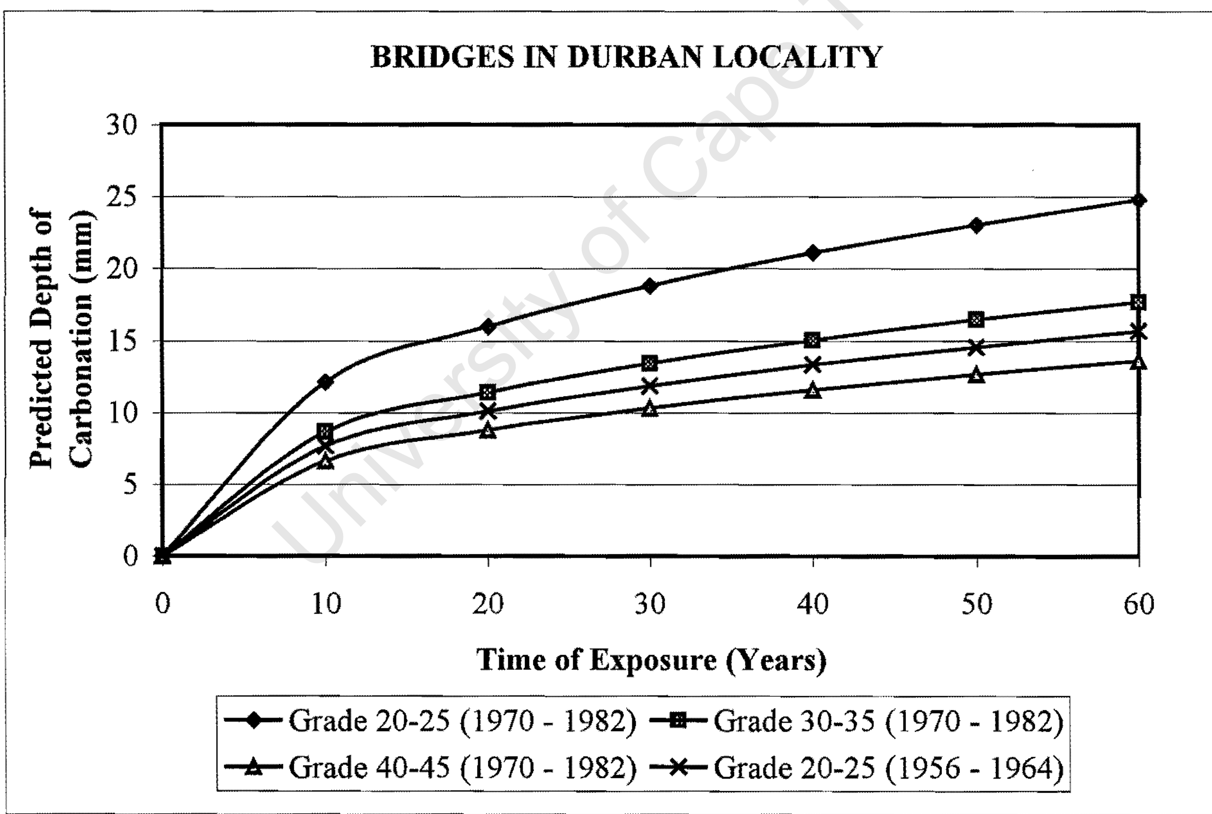
No. of Results: 13

k	**2.09**
Sum of Residual²	**142.1**

BRIDGES IN DURBAN LOCALITY

Comparison Between Sheltered Grade 20-25, 30-35 and 40-45

	Predicted carbonation depth, d_c (mm)			
Time	Grade 20-25	Grade 20-25	Grade 30-35	Grade 40-45
(t)	(1956 - 1964)	(1970 - 1982)	(1970 - 1982)	(1970 - 1982)
(Years)	$d_c = 3.04t^{0.4}$	$d_c = 4.82t^{0.4}$	$d_c = 3.44t^{0.4}$	$d_c = 2.64t^{0.4}$
0	0	0	0	0
10	8	12	9	7
20	10	16	11	9
30	12	19	13	10
40	13	21	15	12
50	15	23	16	13
60	16	25	18	14



APPENDIX F

ANALYSIS OF JOHANNESBURG LOCALITY DATA USING THE METHOD OF LEAST SQUARES

(Data of the Johannesburg Motorway System were obtained from Ballim and Lampacher (1996), while data of the N3 freeway between Heidelberg Road and Geldenhuis Interchanges were provided by Mr. Graham Moore.)

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 20-30 (Johannesburg Motorway System)

Method of Analysis: Method of Least Squares

n	**0.4**

$dc = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
30	20*	15	3.90	15.19	58.47	20.7	-5.7	32.9
30	20*	34	3.90	15.19	132.53	20.7	13.3	175.9
30	20*	35	3.90	15.19	136.43	20.7	14.3	203.4
27	30*	14	3.74	13.97	52.32	19.9	-5.9	34.6
27	30*	10	3.74	13.97	37.37	19.9	-9.9	97.6
27	30*	18	3.74	13.97	67.27	19.9	-1.9	3.5
27	30*	2	3.74	13.97	7.47	19.9	-17.9	319.8
26	30*	20	3.68	13.55	73.62	19.6	0.4	0.2
26	30*	28	3.68	13.55	103.07	19.6	8.4	70.8
26	30*	14	3.68	13.55	51.54	19.6	-5.6	31.2
26	30*	10	3.68	13.55	36.81	19.6	-9.6	91.8
26	30*	16	3.68	13.55	58.90	19.6	-3.6	12.8
26	30*	15	3.68	13.55	55.22	19.6	-4.6	21.0
24	30*	15	3.57	12.71	53.48	19.0	-4.0	15.7
24	30*	4	3.57	12.71	14.26	19.0	-15.0	224.0
24	30*	3	3.57	12.71	10.70	19.0	-16.0	254.9
24	30*	20	3.57	12.71	71.30	19.0	1.0	1.1
24	30*	30	3.57	12.71	106.96	19.0	11.0	121.7
24	**30***	**41**	**3.57**	**12.71**	**146.17**	**19.0**	**22.0**	**485.5**
24	30*	35	3.57	12.71	124.78	19.0	16.0	257.1
24	30*	20	3.57	12.71	71.30	19.0	1.0	1.1
24	30*	20	3.57	12.71	71.30	19.0	1.0	1.1
21	30*	13	3.38	11.42	43.94	18.0	-5.0	24.8
21	30*	15	3.38	11.42	50.70	18.0	-3.0	8.9
20	30*	8	3.31	10.99	26.52	17.6	-9.6	92.8
20	30*	20	3.31	10.99	66.29	17.6	2.4	5.6
20	30*	24	3.31	10.99	79.55	17.6	6.4	40.5
20	30*	23	3.31	10.99	76.23	17.6	5.4	28.8
19	30*	30	3.25	10.54	97.41	17.3	12.7	161.9
19	30*	19	3.25	10.54	61.70	17.3	1.7	3.0
19	30*	19	3.25	10.54	61.70	17.3	1.7	3.0
19	30*	17	3.25	10.54	55.20	17.3	-0.3	0.1
			Sum	**406.12**	**2160.52**	**Mean**	**0.0**	
						Std. Dev	**9.5**	
						+2x(Std. Dev	**19.1**	
						-2x(Std. Dev)	**-19.1**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 32

k	**5.32**	
Sum of Residual^2		**2827.2**

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 20-30 (Johannesburg Motorway System)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.4

$dc = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
30	20*	15	3.90	15.19	58.47	20.0	-5.0	24.6
30	20*	34	3.90	15.19	132.53	20.0	14.0	197.1
30	20*	35	3.90	15.19	136.43	20.0	15.0	226.2
27	30*	14	3.74	13.97	52.32	19.1	-5.1	26.4
27	30*	10	3.74	13.97	37.37	19.1	-9.1	83.5
27	30*	18	3.74	13.97	67.27	19.1	-1.1	1.3
27	30*	2	3.74	13.97	7.47	19.1	-17.1	293.6
26	30*	20	3.68	13.55	73.62	18.8	1.2	1.3
26	30*	28	3.68	13.55	103.07	18.8	9.2	83.7
26	30*	14	3.68	13.55	51.54	18.8	-4.8	23.5
26	30*	10	3.68	13.55	36.81	18.8	-8.8	78.3
26	30*	16	3.68	13.55	58.90	18.8	-2.8	8.1
26	30*	15	3.68	13.55	55.22	18.8	-3.8	14.8
24	30*	15	3.57	12.71	53.48	18.3	-3.3	10.6
24	30*	4	3.57	12.71	14.26	18.3	-14.3	203.2
24	30*	3	3.57	12.71	10.70	18.3	-15.3	232.7
24	30*	20	3.57	12.71	71.30	18.3	1.7	3.0
24	30*	30	3.57	12.71	106.96	18.3	11.7	138.0
24	30*	35	3.57	12.71	124.78	18.3	16.7	280.4
24	30*	20	3.57	12.71	71.30	18.3	1.7	3.0
24	30*	20	3.57	12.71	71.30	18.3	1.7	3.0
21	30*	13	3.38	11.42	43.94	17.3	-4.3	18.5
21	30*	15	3.38	11.42	50.70	17.3	-2.3	5.3
20	30*	8	3.31	10.99	26.52	17.0	-9.0	80.5
20	30*	20	3.31	10.99	66.29	17.0	3.0	9.2
20	30*	24	3.31	10.99	79.55	17.0	7.0	49.4
20	30*	23	3.31	10.99	76.23	17.0	6.0	36.4
19	30*	30	3.25	10.54	97.41	16.6	13.4	178.9
19	30*	19	3.25	10.54	61.70	16.6	2.4	5.6
19	30*	19	3.25	10.54	61.70	16.6	2.4	5.6
19	30*	17	3.25	10.54	55.20	16.6	0.4	0.1
			Sum	**393.41**	**2014.35**	**Mean**	**0.0**	
						Std. Dev	**8.8**	
						+2x(Std. Dev	**17.6**	
						-2x(Std. Dev)	**-17.6**	

* refers to assumed value

No. of Results: 31

k	5.12

Sum of Residual^2	2326.0

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 20-30 (Johannesburg Motorway System)

Method of Analysis: Method of Least Squares

n	0.5

$dc = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20*	15	5.48	30.00	82.16	21.2	-6.2	38.1
30	20*	34	5.48	30.00	186.23	21.2	12.8	164.5
30	20*	35	5.48	30.00	191.70	21.2	13.8	191.1
27	30*	14	5.20	27.00	72.75	20.1	-6.1	37.1
27	30*	10	5.20	27.00	51.96	20.1	-10.1	101.8
27	30*	18	5.20	27.00	93.53	20.1	-2.1	4.4
27	30*	2	5.20	27.00	10.39	20.1	-18.1	327.2
26	30*	20	5.10	26.00	101.98	19.7	0.3	0.1
26	30*	28	5.10	26.00	142.77	19.7	8.3	68.7
26	30*	14	5.10	26.00	71.39	19.7	-5.7	32.6
26	30*	10	5.10	26.00	50.99	19.7	-9.7	94.3
26	30*	16	5.10	26.00	81.58	19.7	-3.7	13.8
26	30*	15	5.10	26.00	76.49	19.7	-4.7	22.2
24	30*	15	4.90	24.00	73.48	18.9	-3.9	15.5
24	30*	4	4.90	24.00	19.60	18.9	-14.9	223.2
24	30*	3	4.90	24.00	14.70	18.9	-15.9	254.1
24	30*	20	4.90	24.00	97.98	18.9	1.1	1.1
24	30*	30	4.90	24.00	146.97	18.9	11.1	122.3
24	**30***	**41**	4.90	24.00	**200.86**	18.9	**22.1**	**486.6**
24	30*	35	4.90	24.00	171.46	18.9	16.1	257.9
24	30*	20	4.90	24.00	97.98	18.9	1.1	1.1
24	30*	20	4.90	24.00	97.98	18.9	1.1	1.1
21	30*	13	4.58	21.00	59.57	17.7	-4.7	22.2
21	30*	15	4.58	21.00	68.74	17.7	-2.7	7.4
20	30*	8	4.47	20.00	35.78	17.3	-9.3	86.3
20	30*	20	4.47	20.00	89.44	17.3	2.7	7.3
20	30*	24	4.47	20.00	107.33	17.3	6.7	45.0
20	30*	23	4.47	20.00	102.86	17.3	5.7	32.6
19	30*	30	4.36	19.00	130.77	16.9	13.1	172.9
19	30*	19	4.36	19.00	82.82	16.9	2.1	4.6
19	30*	19	4.36	19.00	82.82	16.9	2.1	4.6
19	30*	17	4.36	19.00	74.10	16.9	0.1	0.0
			Sum	**768.00**	**2969.15**	**Mean**	**0.1**	
						Std. Dev	**9.6**	
						+2x(Std. Dev	**19.1**	
						-2x(Std. Dev)	**-19.1**	

Note: values in bold are outliers

* refers to assumed value

No. of Results: 32

k	3.87
Sum of Residual^2	**2842.0**

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 20-30 (Johannesburg Motorway System)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20*	15	5.48	30.00	82.16	20.4	-5.4	28.9
30	20*	34	5.48	30.00	186.23	20.4	13.6	185.5
30	20*	35	5.48	30.00	191.70	20.4	14.6	213.7
27	30*	14	5.20	27.00	72.75	19.3	-5.3	28.5
27	30*	10	5.20	27.00	51.96	19.3	-9.3	87.1
27	30*	18	5.20	27.00	93.53	19.3	-1.3	1.8
27	30*	2	5.20	27.00	10.39	19.3	-17.3	300.5
26	30*	20	5.10	26.00	101.98	19.0	1.0	1.1
26	30*	28	5.10	26.00	142.77	19.0	9.0	81.5
26	30*	14	5.10	26.00	71.39	19.0	-5.0	24.7
26	30*	10	5.10	26.00	50.99	19.0	-9.0	80.5
26	30*	16	5.10	26.00	81.58	19.0	-3.0	8.8
26	30*	15	5.10	26.00	76.49	19.0	-4.0	15.8
24	30*	15	4.90	24.00	73.48	18.2	-3.2	10.4
24	30*	4	4.90	24.00	19.60	18.2	-14.2	202.4
24	30*	3	4.90	24.00	14.70	18.2	-15.2	231.9
24	30*	20	4.90	24.00	97.98	18.2	1.8	3.1
24	30*	30	4.90	24.00	146.97	18.2	11.8	138.6
24	30*	35	4.90	24.00	171.46	18.2	16.8	281.3
24	30*	20	4.90	24.00	97.98	18.2	1.8	3.1
24	30*	20	4.90	24.00	97.98	18.2	1.8	3.1
21	30*	13	4.58	21.00	59.57	17.1	-4.1	16.4
21	30*	15	4.58	21.00	68.74	17.1	-2.1	4.2
20	30*	8	4.47	20.00	35.78	16.6	-8.6	74.7
20	30*	20	4.47	20.00	89.44	16.6	3.4	11.3
20	30*	24	4.47	20.00	107.33	16.6	7.4	54.2
20	30*	23	4.47	20.00	102.86	16.6	6.4	40.4
19	30*	30	4.36	19.00	130.77	16.2	13.8	189.9
19	30*	19	4.36	19.00	82.82	16.2	2.8	7.7
19	30*	19	4.36	19.00	82.82	16.2	2.8	7.7
19	30*	17	4.36	19.00	74.10	16.2	0.8	0.6
			Sum	**744.00**	**2768.30**	**Mean**	**0.1**	
						Std. Dev	**8.8**	
						+2x(Std. Dev	**17.7**	
						-2x(Std. Dev)	**-17.7**	

* refers to assumed value

No. of Results: 31

k	3.72
Sum of Residual^2	**2339.7**

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 20-30 (the Johannesburg Motorway System)

Method of Analysis: Method of Least Squares

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	**Predicted**	**Residual**	**Residual²**
30	20*	18	3.90	15.19	70.17	17.7	0.3	0.1
24	30*	9	3.57	12.71	32.09	16.2	-7.2	52.1
24	30*	11	3.57	12.71	39.22	16.2	-5.2	27.3
24	30*	12	3.57	12.71	42.78	16.2	-4.2	17.8
24	30*	11	3.57	12.71	39.22	16.2	-5.2	27.3
24	30*	12	3.57	12.71	42.78	16.2	-4.2	17.8
24	30*	2	3.57	12.71	7.13	16.2	-14.2	202.2
24	**30***	**35**	**3.57**	**12.71**	**124.78**	**16.2**	**18.8**	352.7
24	30*	25	3.57	12.71	89.13	16.2	8.8	77.1
24	30*	20	3.57	12.71	71.30	16.2	3.8	14.3
24	30*	19	3.57	12.71	67.74	16.2	2.8	7.7
21	30*	17	3.38	11.42	57.46	15.4	1.6	2.6
21	30*	20	3.38	11.42	67.60	15.4	4.6	21.4
			Sum	**165.15**	**751.39**	**Mean**	**0.0**	
						Std. Dev	**8.3**	
						+2x(Std. Dev	**16.5**	
						-2x(Std. Dev)	**-16.5**	
					k	**4.55**		
					Sum of Residual²		**820.3**	

Note: values in bold are outliers

* refers to assumed value

No. of Results: 13

(After the 1st Elimination of Outliers)

n	0.4	$d_c = kt^{0.4}$						
Age (t)	**Grade**	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	**Predicted**	**Residual**	**Residual²**
30	20*	18	3.90	15.19	70.17	16.0	2.0	3.9
24	30*	9	3.57	12.71	32.09	14.7	-5.7	32.0
24	30*	11	3.57	12.71	39.22	14.7	-3.7	13.4
24	30*	12	3.57	12.71	42.78	14.7	-2.7	7.0
24	30*	11	3.57	12.71	39.22	14.7	-3.7	13.4
24	30*	12	3.57	12.71	42.78	14.7	-2.7	7.0
24	**30***	**2**	**3.57**	**12.71**	**7.13**	**14.7**	**-12.7**	**160.2**
24	30*	25	3.57	12.71	89.13	14.7	10.3	107.0
24	30*	20	3.57	12.71	71.30	14.7	5.3	28.6
24	30*	19	3.57	12.71	67.74	14.7	4.3	18.9
21	30*	17	3.38	11.42	57.46	13.9	3.1	9.7
21	30*	20	3.38	11.42	67.60	13.9	6.1	37.3
			Sum	**152.44**	**626.61**	**Mean**	**0.0**	
						Std. Dev	**6.3**	
						+2x(Std. Dev	**12.6**	
						-2x(Std. Dev)	**-12.6**	
					k	**4.11**		
					Sum of Residual²		**438.3**	

Note: values in bold are outliers

* refers to assumed value

No. of Results: 12

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 20-30 (the Johannesburg Motorway System)

Method of Analysis: Method of Least Squares

(After the 1st Elimination of Outliers)

n	0.4	$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
30	20*	18	3.90	15.19	70.17	17.3	0.7	0.5
24	30*	9	3.57	12.71	32.09	15.8	-6.8	46.3
24	30*	11	3.57	12.71	39.22	15.8	-4.8	23.1
24	30*	12	3.57	12.71	42.78	15.8	-3.8	14.5
24	30*	11	3.57	12.71	39.22	15.8	-4.8	23.1
24	30*	12	3.57	12.71	42.78	15.8	-3.8	14.5
24	30*	25	3.57	12.71	89.13	15.8	9.2	84.5
24	30*	20	3.57	12.71	71.30	15.8	4.2	17.6
24	30*	19	3.57	12.71	67.74	15.8	3.2	10.2
21	30*	17	3.38	11.42	57.46	15.0	2.0	4.1
21	30*	20	3.38	11.42	67.60	15.0	5.0	25.2
			Sum	**139.73**	**619.48**	**Mean**	**0.0**	
						Std. Dev	**5.1**	
						+2x(Std. Dev	**10.3**	
						-2x(Std. Dev)	**-10.3**	
					k	**4.43**		
					Sum of Residual^2		**263.6**	

* refers to assumed value

No. of Results: 11

n	0.5	$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20*	18	5.48	30.00	98.59	18.1	-0.1	0.0
24	30*	9	4.90	24.00	44.09	16.2	-7.2	52.0
24	30*	11	4.90	24.00	53.89	16.2	-5.2	27.1
24	30*	12	4.90	24.00	58.79	16.2	-4.2	17.7
24	30*	11	4.90	24.00	53.89	16.2	-5.2	27.1
24	30*	12	4.90	24.00	58.79	16.2	-4.2	17.7
24	30*	2	4.90	24.00	9.80	16.2	-14.2	201.9
24	**30***	**35**	4.90	24.00	**171.46**	16.2	**18.8**	353.0
24	30*	25	4.90	24.00	122.47	16.2	8.8	77.3
24	30*	20	4.90	24.00	97.98	16.2	3.8	14.4
24	30*	19	4.90	24.00	93.08	16.2	2.8	7.8
21	30*	17	4.58	21.00	77.90	15.2	1.8	3.4
21	30*	20	4.58	21.00	91.65	15.2	4.8	23.4
			Sum	**312.00**	**1032.39**	**Mean**	**0.0**	
						Std. Dev	**8.3**	
						+2x(Std. Dev	**16.6**	
						-2x(Std. Dev)	**-16.6**	
					k	**3.31**		
					Sum of Residual^2		**822.9**	

Note: values in bold are outliers

* refers to assumed value

No. of Results: 13

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 20-30 (the Johannesburg Motorway System)

Method of Analysis: Method of Least Squares

(After the 1st Elimination of Outliers)

n	0.5	$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20*	18	5.48	30.00	98.59	16.4	1.6	2.6
24	30*	9	4.90	24.00	44.09	14.6	-5.6	31.9
24	30*	11	4.90	24.00	53.89	14.6	-3.6	13.3
24	30*	12	4.90	24.00	58.79	14.6	-2.6	7.0
24	30*	11	4.90	24.00	53.89	14.6	-3.6	13.3
24	30*	12	4.90	24.00	58.79	14.6	-2.6	7.0
24	30*	2	4.90	24.00	9.80	14.6	-12.6	159.9
24	30*	25	4.90	24.00	122.47	14.6	10.4	107.2
24	30*	20	4.90	24.00	97.98	14.6	5.4	28.7
24	30*	19	4.90	24.00	93.08	14.6	4.4	19.0
21	30*	17	4.58	21.00	77.90	13.7	3.3	10.9
21	30*	20	4.58	21.00	91.65	13.7	6.3	39.7
			Sum	**288.00**	**860.92**	**Mean**	**0.0**	
						Std. Dev	**6.3**	
						+2x(Std. Dev	**12.7**	
						-2x(Std. Dev)	**-12.7**	

* refers to assumed value

No. of Results: 12

k	2.99	
Sum of Residual^2		**440.4**

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 25-30 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
22	25*	18	3.44	11.86	61.98	18.7	-0.7	0.4
22	25*	19	3.44	11.86	65.42	18.7	0.3	0.1
23	25*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	25*	17	3.51	12.29	59.59	19.0	-2.0	4.0
23	25*	19	3.51	12.29	66.60	19.0	0.0	0.0
23	25*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	**25***	**8**	**3.51**	**12.29**	**28.04**	**19.0**	**-11.0**	**121.0**
23	25*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	25*	14	3.51	12.29	49.07	19.0	-5.0	25.0
23	25*	11	3.51	12.29	38.56	19.0	-8.0	64.0
23	25*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	25*	10	3.51	12.29	35.05	19.0	-9.0	81.0
23	25*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	25*	24	3.51	12.29	84.12	19.0	5.0	25.0
28	25*	16	3.79	14.38	60.67	20.6	-4.6	20.8
28	25*	17	3.79	14.38	64.46	20.6	-3.6	12.6
23	25*	15	3.51	12.29	52.58	19.0	-4.0	16.0
23	25*	25	3.51	12.29	87.63	19.0	6.0	36.0
28	25*	14	3.79	14.38	53.09	20.6	-6.6	43.0
28	25*	17	3.79	14.38	64.46	20.6	-3.6	12.6
23	25*	13	3.51	12.29	45.57	19.0	-6.0	36.0
23	30*	23	3.51	12.29	80.62	19.0	4.0	16.0
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	26	3.51	12.29	91.13	19.0	7.0	49.0
23	30*	25	3.51	12.29	87.63	19.0	6.0	36.0
23	30*	24	3.51	12.29	84.12	19.0	5.0	25.0
23	30*	24	3.51	12.29	84.12	19.0	5.0	25.0
23	30*	22	3.51	12.29	77.11	19.0	3.0	9.0
28	30*	30	3.79	14.38	113.76	20.6	9.4	89.2
28	30*	26	3.79	14.38	98.59	20.6	5.4	29.6
28	30*	31	3.79	14.38	117.55	20.6	10.4	109.1
28	30*	23	3.79	14.38	87.21	20.6	2.4	6.0
23	30*	11	3.51	12.29	38.56	19.0	-8.0	64.0
			Sum	**433.59**	**2350.44**	**Mean**	**0.0**	
						Std. Dev	**5.4**	
						+2x(Std. Dev	**10.9**	
						-2x(Std. Dev)	**-10.9**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 34

k	5.42

Sum of Residual^2	971.5

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 25-30 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
22	25*	18	3.44	11.86	61.98	19.0	-1.0	1.0
22	25*	19	3.44	11.86	65.42	19.0	0.0	0.0
23	25*	21	3.51	12.29	73.61	19.3	1.7	2.8
23	25*	17	3.51	12.29	59.59	19.3	-2.3	5.4
23	25*	19	3.51	12.29	66.60	19.3	-0.3	0.1
23	25*	21	3.51	12.29	73.61	19.3	1.7	2.8
23	25*	21	3.51	12.29	73.61	19.3	1.7	2.8
23	25*	14	3.51	12.29	49.07	19.3	-5.3	28.3
23	25*	11	3.51	12.29	38.56	19.3	-8.3	69.2
23	25*	18	3.51	12.29	63.09	19.3	-1.3	1.7
23	25*	10	3.51	12.29	35.05	19.3	-9.3	86.9
23	25*	18	3.51	12.29	63.09	19.3	-1.3	1.7
23	25*	24	3.51	12.29	84.12	19.3	4.7	21.9
28	25*	16	3.79	14.38	60.67	20.9	-4.9	24.0
28	25*	17	3.79	14.38	64.46	20.9	-3.9	15.2
23	25*	15	3.51	12.29	52.58	19.3	-4.3	18.7
23	25*	25	3.51	12.29	87.63	19.3	5.7	32.2
28	25*	14	3.79	14.38	53.09	20.9	-6.9	47.6
28	25*	17	3.79	14.38	64.46	20.9	-3.9	15.2
23	25*	13	3.51	12.29	45.57	19.3	-6.3	40.0
23	30*	23	3.51	12.29	80.62	19.3	3.7	13.5
23	30*	18	3.51	12.29	63.09	19.3	-1.3	1.7
23	30*	18	3.51	12.29	63.09	19.3	-1.3	1.7
23	30*	26	3.51	12.29	91.13	19.3	6.7	44.6
23	30*	25	3.51	12.29	87.63	19.3	5.7	32.2
23	30*	24	3.51	12.29	84.12	19.3	4.7	21.9
23	30*	24	3.51	12.29	84.12	19.3	4.7	21.9
23	30*	22	3.51	12.29	77.11	19.3	2.7	7.2
28	30*	30	3.79	14.38	113.76	20.9	9.1	82.8
28	30*	26	3.79	14.38	98.59	20.9	5.1	26.0
28	30*	31	3.79	14.38	117.55	20.9	10.1	102.0
28	30*	23	3.79	14.38	87.21	20.9	2.1	4.4
23	30*	11	3.51	12.29	38.56	19.3	-8.3	69.2
			Sum	**421.30**	**2322.40**	**Mean**	**0.0**	
						Std. Dev	**5.1**	
						+2x(Std. Dev	**10.3**	
						-2x(Std. Dev)	**-10.3**	

* refers to assumed value

No. of Results: 33

k	5.51

Sum of Residual^2	846.9

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 25-30 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
22	25*	18	4.69	22.00	84.43	18.5	-0.5	0.2
22	25*	19	4.69	22.00	89.12	18.5	0.5	0.3
23	25*	21	4.80	23.00	100.71	18.9	2.1	4.4
23	25*	17	4.80	23.00	81.53	18.9	-1.9	3.6
23	25*	19	4.80	23.00	91.12	18.9	0.1	0.0
23	25*	21	4.80	23.00	100.71	18.9	2.1	4.4
23	**25***	**8**	**4.80**	**23.00**	**38.37**	**18.9**	**-10.9**	**119.0**
23	25*	21	4.80	23.00	100.71	18.9	2.1	4.4
23	25*	14	4.80	23.00	67.14	18.9	-4.9	24.1
23	25*	11	4.80	23.00	52.75	18.9	-7.9	62.6
23	25*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	25*	10	4.80	23.00	47.96	18.9	-8.9	79.4
23	25*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	25*	24	4.80	23.00	115.10	18.9	5.1	25.9
28	25*	16	5.29	28.00	84.66	20.9	-4.9	23.7
28	25*	17	5.29	28.00	89.96	20.9	-3.9	14.9
23	25*	15	4.80	23.00	71.94	18.9	-3.9	15.3
23	25*	25	4.80	23.00	119.90	18.9	6.1	37.1
28	25*	14	5.29	28.00	74.08	20.9	-6.9	47.1
28	25*	17	5.29	28.00	89.96	20.9	-3.9	14.9
23	25*	13	4.80	23.00	62.35	18.9	-5.9	34.9
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.7
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	26	4.80	23.00	124.69	18.9	7.1	50.3
23	30*	25	4.80	23.00	119.90	18.9	6.1	37.1
23	30*	24	4.80	23.00	115.10	18.9	5.1	25.9
23	30*	24	4.80	23.00	115.10	18.9	5.1	25.9
23	30*	22	4.80	23.00	105.51	18.9	3.1	9.6
28	30*	30	5.29	28.00	158.75	20.9	9.1	83.5
28	30*	26	5.29	28.00	137.58	20.9	5.1	26.4
28	30*	31	5.29	28.00	164.04	20.9	10.1	102.7
28	30*	23	5.29	28.00	121.70	20.9	2.1	4.6
23	30*	11	4.80	23.00	52.75	18.9	-7.9	62.6
			Sum	**820.00**	**3233.21**	**Mean**	**0.0**	
						Std. Dev	**5.4**	
						+2x(Std. Dev	**10.8**	
						-2x(Std. Dev)	**-10.8**	

Note: values in bold are outliers
* refers to assumed value

No. of Results: 34

k	3.94

Sum of Residual^2	964.7

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 25-30 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
22	25*	18	4.69	22.00	84.43	18.8	-0.8	0.6
22	25*	19	4.69	22.00	89.12	18.8	0.2	0.0
23	25*	21	4.80	23.00	100.71	19.2	1.8	3.2
23	25*	17	4.80	23.00	81.53	19.2	-2.2	4.9
23	25*	19	4.80	23.00	91.12	19.2	-0.2	0.1
23	25*	21	4.80	23.00	100.71	19.2	1.8	3.2
23	25*	21	4.80	23.00	100.71	19.2	1.8	3.2
23	25*	14	4.80	23.00	67.14	19.2	-5.2	27.3
23	25*	11	4.80	23.00	52.75	19.2	-8.2	67.6
23	25*	18	4.80	23.00	86.32	19.2	-1.2	1.5
23	25*	10	4.80	23.00	47.96	19.2	-9.2	85.1
23	25*	18	4.80	23.00	86.32	19.2	-1.2	1.5
23	25*	24	4.80	23.00	115.10	19.2	4.8	22.8
28	25*	16	5.29	28.00	84.66	21.2	-5.2	27.2
28	25*	17	5.29	28.00	89.96	21.2	-4.2	17.7
23	25*	15	4.80	23.00	71.94	19.2	-4.2	17.8
23	25*	25	4.80	23.00	119.90	19.2	5.8	33.4
28	25*	14	5.29	28.00	74.08	21.2	-7.2	52.0
28	25*	17	5.29	28.00	89.96	21.2	-4.2	17.7
23	25*	13	4.80	23.00	62.35	19.2	-6.2	38.7
23	30*	23	4.80	23.00	110.30	19.2	3.8	14.3
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.5
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.5
23	30*	26	4.80	23.00	124.69	19.2	6.8	45.9
23	30*	25	4.80	23.00	119.90	19.2	5.8	33.4
23	30*	24	4.80	23.00	115.10	19.2	4.8	22.8
23	30*	24	4.80	23.00	115.10	19.2	4.8	22.8
23	30*	22	4.80	23.00	105.51	19.2	2.8	7.7
28	30*	30	5.29	28.00	158.75	21.2	8.8	77.2
28	30*	26	5.29	28.00	137.58	21.2	4.8	22.9
28	30*	31	5.29	28.00	164.04	21.2	9.8	95.8
28	30*	23	5.29	28.00	121.70	21.2	1.8	3.2
23	30*	11	4.80	23.00	52.75	19.2	-8.2	67.6
			Sum	**797.00**	**3194.84**	**Mean**	**0.0**	
						Std. Dev	**5.1**	
						+2x(Std. Dev	**10.3**	
						-2x(Std. Dev)	**-10.3**	

* refers to assumed value

No. of Results: 33

k	4.01

Sum of Residual^2	842.2

BRIDGES IN JOHANNESBURG LOCALITY

Exposed Grade 35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\, t_i^{0.4}$	Predicted	Residual	Residual^2
22	35*	23	3.44	11.86	79.19	15.2	7.8	60.7
23	35*	17	3.51	12.29	59.59	15.5	1.5	2.3
23	35*	23	3.51	12.29	80.62	15.5	7.5	56.5
23	35*	10	3.51	12.29	35.05	15.5	-5.5	30.1
23	35*	23	3.51	12.29	80.62	15.5	7.5	56.5
23	35*	11	3.51	12.29	38.56	15.5	-4.5	20.1
23	35*	11	3.51	12.29	38.56	15.5	-4.5	20.1
28	35*	15	3.79	14.38	56.88	16.8	-1.8	3.1
28	35*	17	3.79	14.38	64.46	16.8	0.2	0.1
28	35*	14	3.79	14.38	53.09	16.8	-2.8	7.6
28	35*	12	3.79	14.38	45.50	16.8	-4.8	22.6
			Sum	**143.08**	**632.11**	**Mean**	**0.1**	
						Std. Dev	**5.3**	
						+2x(Std. Dev	**10.6**	
						-2x(Std. Dev)	**-10.6**	

* refers to assumed value

No. of Results: 11

k	4.42
Sum of Residual^2	**279.5**

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
22	35*	23	4.69	22.00	107.88	15.0	8.0	63.9
23	35*	17	4.80	23.00	81.53	15.3	1.7	2.7
23	35*	23	4.80	23.00	110.30	15.3	7.7	58.6
23	35*	10	4.80	23.00	47.96	15.3	-5.3	28.6
23	35*	23	4.80	23.00	110.30	15.3	7.7	58.6
23	35*	11	4.80	23.00	52.75	15.3	-4.3	18.9
23	35*	11	4.80	23.00	52.75	15.3	-4.3	18.9
28	35*	15	5.29	28.00	79.37	16.9	-1.9	3.7
28	35*	17	5.29	28.00	89.96	16.9	0.1	0.0
28	35*	14	5.29	28.00	74.08	16.9	-2.9	8.6
28	35*	12	5.29	28.00	63.50	16.9	-4.9	24.3
			Sum	**272.00**	**870.39**	**Mean**	**0.1**	
						Std. Dev	**5.4**	
						+2x(Std. Dev	**10.7**	
						-2x(Std. Dev)	**-10.7**	

* refers to assumed value

No. of Results: 11

k	3.20
Sum of Residual^2	**286.8**

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\,t_i^{0.4}$	Predicted	Residual	Residual^2
22	35*	15	3.44	11.86	51.65	18.6	-3.6	12.9
23	35*	14	3.51	12.29	49.07	18.9	-4.9	24.2
23	35*	16	3.51	12.29	56.08	18.9	-2.9	8.5
23	35*	18	3.51	12.29	63.09	18.9	-0.9	0.8
23	**35***	**9**	**3.51**	**12.29**	**31.55**	**18.9**	**-9.9**	98.4
23	**35***	**8**	**3.51**	**12.29**	**28.04**	**18.9**	**-10.9**	119.3
23	35*	14	3.51	12.29	49.07	18.9	-4.9	24.2
23	35*	15	3.51	12.29	52.58	18.9	-3.9	15.4
23	35*	16	3.51	12.29	56.08	18.9	-2.9	8.5
23	35*	13	3.51	12.29	45.57	18.9	-5.9	35.1
23	35*	23	3.51	12.29	80.62	18.9	4.1	16.6
23	35*	21	3.51	12.29	73.61	18.9	2.1	4.3
23	35*	23	3.51	12.29	80.62	18.9	4.1	16.6
28	35*	19	3.79	14.38	72.05	20.5	-1.5	2.2
28	35*	20	3.79	14.38	75.84	20.5	-0.5	0.2
22	30*	27	3.44	11.86	92.97	18.6	8.4	70.8
23	30*	23	3.51	12.29	80.62	18.9	4.1	16.6
23	30*	23	3.51	12.29	80.62	18.9	4.1	16.6
23	30*	13	3.51	12.29	45.57	18.9	-5.9	35.1
23	30*	17	3.51	12.29	59.59	18.9	-1.9	3.7
23	30*	18	3.51	12.29	63.09	18.9	-0.9	0.8
23	30*	20	3.51	12.29	70.10	18.9	1.1	1.2
23	30*	21	3.51	12.29	73.61	18.9	2.1	4.3
23	30*	24	3.51	12.29	84.12	18.9	5.1	25.8
23	30*	18	3.51	12.29	63.09	18.9	-0.9	0.8
23	30*	18	3.51	12.29	63.09	18.9	-0.9	0.8
23	30*	18	3.51	12.29	63.09	18.9	-0.9	0.8
23	30*	26	3.51	12.29	91.13	18.9	7.1	50.1
23	**35***	**29**	**3.51**	**12.29**	**101.65**	**18.9**	**10.1**	101.6
28	35*	22	3.79	14.38	83.42	20.5	1.5	2.3
28	35*	24	3.79	14.38	91.01	20.5	3.5	12.5
23	30*	23	3.51	12.29	80.62	18.9	4.1	16.6
23	35*	19	3.51	12.29	66.60	18.9	0.1	0.0
23	35*	22	3.51	12.29	77.11	18.9	3.1	9.5
23	30*	17	3.51	12.29	59.59	18.9	-1.9	3.7
23	30*	14	3.51	12.29	49.07	18.9	-4.9	24.2
22	30*	26	3.44	11.86	89.52	18.6	7.4	54.9
23	30*	21	3.51	12.29	73.61	18.9	2.1	4.3
23	30*	22	3.51	12.29	77.11	18.9	3.1	9.5
23	30*	13	3.51	12.29	45.57	18.9	-5.9	35.1
			Sum	**498.50**	**2691.02**	**Mean**	**0.0**	
						Std. Dev	**4.8**	
						+2x(Std. Dev	**9.5**	
						-2x(Std. Dev)	**-9.5**	

Note: values in bold are outliers

* refers to assumed values

No. of Results: 40

k	5.40
Sum of Residual^2	**889.1**

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
22	35*	15	3.44	11.86	51.65	18.9	-3.9	15.0
23	35*	14	3.51	12.29	49.07	19.2	-5.2	27.1
23	35*	16	3.51	12.29	56.08	19.2	-3.2	10.3
23	35*	18	3.51	12.29	63.09	19.2	-1.2	1.5
23	35*	14	3.51	12.29	49.07	19.2	-5.2	27.1
23	35*	15	3.51	12.29	52.58	19.2	-4.2	17.7
23	35*	16	3.51	12.29	56.08	19.2	-3.2	10.3
23	35*	13	3.51	12.29	45.57	19.2	-6.2	38.5
23	35*	23	3.51	12.29	80.62	19.2	3.8	14.4
23	35*	21	3.51	12.29	73.61	19.2	1.8	3.2
23	35*	23	3.51	12.29	80.62	19.2	3.8	14.4
28	35*	19	3.79	14.38	72.05	20.8	-1.8	3.2
28	35*	20	3.79	14.38	75.84	20.8	-0.8	0.6
22	**30***	**27**	**3.44**	**11.86**	**92.97**	**18.9**	**8.1**	**66.1**
23	30*	23	3.51	12.29	80.62	19.2	3.8	14.4
23	30*	23	3.51	12.29	80.62	19.2	3.8	14.4
23	30*	13	3.51	12.29	45.57	19.2	-6.2	38.5
23	30*	17	3.51	12.29	59.59	19.2	-2.2	4.9
23	30*	18	3.51	12.29	63.09	19.2	-1.2	1.5
23	30*	20	3.51	12.29	70.10	19.2	0.8	0.6
23	30*	21	3.51	12.29	73.61	19.2	1.8	3.2
23	30*	24	3.51	12.29	84.12	19.2	4.8	23.0
23	30*	18	3.51	12.29	63.09	19.2	-1.2	1.5
23	30*	18	3.51	12.29	63.09	19.2	-1.2	1.5
23	30*	18	3.51	12.29	63.09	19.2	-1.2	1.5
23	30*	26	3.51	12.29	91.13	19.2	6.8	46.1
28	35*	22	3.79	14.38	83.42	20.8	1.2	1.5
28	35*	24	3.79	14.38	91.01	20.8	3.2	10.4
23	30*	23	3.51	12.29	80.62	19.2	3.8	14.4
23	35*	19	3.51	12.29	66.60	19.2	-0.2	0.0
23	35*	22	3.51	12.29	77.11	19.2	2.8	7.8
23	30*	17	3.51	12.29	59.59	19.2	-2.2	4.9
23	30*	14	3.51	12.29	49.07	19.2	-5.2	27.1
22	30*	26	3.44	11.86	89.52	18.9	7.1	50.9
23	30*	21	3.51	12.29	73.61	19.2	1.8	3.2
23	30*	22	3.51	12.29	77.11	19.2	2.8	7.8
23	30*	13	3.51	12.29	45.57	19.2	-6.2	38.5
			Sum	**461.64**	**2529.79**	**Mean**	**0.0**	
						Std. Dev	**4.0**	
						+2x(Std. Dev	**7.9**	
						-2x(Std. Dev)	**-7.9**	

Note: values in bold are outliers
* refers to assumed values

No. of Results: 37

k	5.48
Sum of Residual^2	**566.8**

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.4

$d_c = kt^{0.4}$

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}\ t_i^{0.4}$	Predicted	Residual	Residual^2
22	35*	15	3.44	11.86	51.65	18.7	-3.7	13.4
23	35*	14	3.51	12.29	49.07	19.0	-5.0	24.9
23	35*	16	3.51	12.29	56.08	19.0	-3.0	8.9
23	35*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	35*	14	3.51	12.29	49.07	19.0	-5.0	24.9
23	35*	15	3.51	12.29	52.58	19.0	-4.0	15.9
23	35*	16	3.51	12.29	56.08	19.0	-3.0	8.9
23	35*	13	3.51	12.29	45.57	19.0	-6.0	35.9
23	35*	23	3.51	12.29	80.62	19.0	4.0	16.1
23	35*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	35*	23	3.51	12.29	80.62	19.0	4.0	16.1
28	35*	19	3.79	14.38	72.05	20.5	-1.5	2.4
28	35*	20	3.79	14.38	75.84	20.5	-0.5	0.3
23	30*	23	3.51	12.29	80.62	19.0	4.0	16.1
23	30*	23	3.51	12.29	80.62	19.0	4.0	16.1
23	30*	13	3.51	12.29	45.57	19.0	-6.0	35.9
23	30*	17	3.51	12.29	59.59	19.0	-2.0	4.0
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	20	3.51	12.29	70.10	19.0	1.0	1.0
23	30*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	30*	24	3.51	12.29	84.12	19.0	5.0	25.1
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	18	3.51	12.29	63.09	19.0	-1.0	1.0
23	30*	26	3.51	12.29	91.13	19.0	7.0	49.1
28	35*	22	3.79	14.38	83.42	20.5	1.5	2.1
28	35*	24	3.79	14.38	91.01	20.5	3.5	11.9
23	30*	23	3.51	12.29	80.62	19.0	4.0	16.1
23	35*	19	3.51	12.29	66.60	19.0	0.0	0.0
23	35*	22	3.51	12.29	77.11	19.0	3.0	9.1
23	30*	17	3.51	12.29	59.59	19.0	-2.0	4.0
23	30*	14	3.51	12.29	49.07	19.0	-5.0	24.9
22	30*	26	3.44	11.86	89.52	18.7	7.3	54.0
23	30*	21	3.51	12.29	73.61	19.0	2.0	4.0
23	30*	22	3.51	12.29	77.11	19.0	3.0	9.1
23	30*	13	3.51	12.29	45.57	19.0	-6.0	35.9
			Sum	**449.78**	**2436.82**	**Mean**	**0.0**	
						Std. Dev	**3.8**	
						+2x(Std. Dev	**7.6**	
						-2x(Std. Dev)	**-7.6**	

* refers to asumed value

No. of Results: 36

k	5.42
Sum of Residual^2	**498.9**

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
22	35*	15	4.69	22.00	70.36	18.5	-3.5	12.0
23	35*	14	4.80	23.00	67.14	18.9	-4.9	23.8
23	35*	16	4.80	23.00	76.73	18.9	-2.9	8.3
23	35*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	**35***	**9**	**4.80**	**23.00**	**43.16**	**18.9**	**-9.9**	97.7
23	**35***	**8**	**4.80**	**23.00**	**38.37**	**18.9**	**-10.9**	118.4
23	35*	14	4.80	23.00	67.14	18.9	-4.9	23.8
23	35*	15	4.80	23.00	71.94	18.9	-3.9	15.1
23	35*	16	4.80	23.00	76.73	18.9	-2.9	8.3
23	35*	13	4.80	23.00	62.35	18.9	-5.9	34.6
23	35*	23	4.80	23.00	110.30	18.9	4.1	16.9
23	35*	21	4.80	23.00	100.71	18.9	2.1	4.5
23	35*	23	4.80	23.00	110.30	18.9	4.1	16.9
28	35*	19	5.29	28.00	100.54	20.8	-1.8	3.4
28	35*	20	5.29	28.00	105.83	20.8	-0.8	0.7
22	30*	27	4.69	22.00	126.64	18.5	8.5	72.8
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.9
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.9
23	30*	13	4.80	23.00	62.35	18.9	-5.9	34.6
23	30*	17	4.80	23.00	81.53	18.9	-1.9	3.5
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	20	4.80	23.00	95.92	18.9	1.1	1.2
23	30*	21	4.80	23.00	100.71	18.9	2.1	4.5
23	30*	24	4.80	23.00	115.10	18.9	5.1	26.2
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.8
23	30*	26	4.80	23.00	124.69	18.9	7.1	50.6
23	**35***	**29**	**4.80**	**23.00**	**139.08**	**18.9**	**10.1**	102.3
28	35*	22	5.29	28.00	116.41	20.8	1.2	1.4
28	35*	24	5.29	28.00	127.00	20.8	3.2	10.0
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.9
23	35*	19	4.80	23.00	91.12	18.9	0.1	0.0
23	35*	22	4.80	23.00	105.51	18.9	3.1	9.7
23	30*	17	4.80	23.00	81.53	18.9	-1.9	3.5
23	30*	14	4.80	23.00	67.14	18.9	-4.9	23.8
22	30*	26	4.69	22.00	121.95	18.5	7.5	56.7
23	30*	21	4.80	23.00	100.71	18.9	2.1	4.5
23	30*	22	4.80	23.00	105.51	18.9	3.1	9.7
23	30*	13	4.80	23.00	62.35	18.9	-5.9	34.6
			Sum	**937.00**	**3689.39**	**Mean**	**0.0**	
						Std. Dev	**4.8**	
						+2x(Std. Dev	**9.6**	
						-2x(Std. Dev)	**-9.6**	

Note: values in bold are outliers

* refers to assumed values

No. of Results: 40

k	3.94
Sum of Residual^2	**889.2**

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
22	35*	15	4.69	22.00	70.36	18.7	-3.7	14.0
23	35*	14	4.80	23.00	67.14	19.2	-5.2	26.7
23	35*	16	4.80	23.00	76.73	19.2	-3.2	10.0
23	35*	18	4.80	23.00	86.32	19.2	-1.2	1.4
23	35*	14	4.80	23.00	67.14	19.2	-5.2	26.7
23	35*	15	4.80	23.00	71.94	19.2	-4.2	17.4
23	35*	16	4.80	23.00	76.73	19.2	-3.2	10.0
23	35*	13	4.80	23.00	62.35	19.2	-6.2	38.0
23	35*	23	4.80	23.00	110.30	19.2	3.8	14.7
23	35*	21	4.80	23.00	100.71	19.2	1.8	3.4
23	35*	23	4.80	23.00	110.30	19.2	3.8	14.7
28	35*	19	5.29	28.00	100.54	21.1	-2.1	4.6
28	35*	20	5.29	28.00	105.83	21.1	-1.1	1.3
22	**30***	**27**	**4.69**	**22.00**	**126.64**	**18.7**	**8.3**	**68.2**
23	30*	23	4.80	23.00	110.30	19.2	3.8	14.7
23	30*	23	4.80	23.00	110.30	19.2	3.8	14.7
23	30*	13	4.80	23.00	62.35	19.2	-6.2	38.0
23	30*	17	4.80	23.00	81.53	19.2	-2.2	4.7
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.4
23	30*	20	4.80	23.00	95.92	19.2	0.8	0.7
23	30*	21	4.80	23.00	100.71	19.2	1.8	3.4
23	30*	24	4.80	23.00	115.10	19.2	4.8	23.4
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.4
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.4
23	30*	18	4.80	23.00	86.32	19.2	-1.2	1.4
23	30*	26	4.80	23.00	124.69	19.2	6.8	46.7
28	35*	22	5.29	28.00	116.41	21.1	0.9	0.7
28	35*	24	5.29	28.00	127.00	21.1	2.9	8.1
23	30*	23	4.80	23.00	110.30	19.2	3.8	14.7
23	35*	19	4.80	23.00	91.12	19.2	-0.2	0.0
23	35*	22	4.80	23.00	105.51	19.2	2.8	8.0
23	30*	17	4.80	23.00	81.53	19.2	-2.2	4.7
23	30*	14	4.80	23.00	67.14	19.2	-5.2	26.7
22	30*	26	4.69	22.00	121.95	18.7	7.3	52.6
23	30*	21	4.80	23.00	100.71	19.2	1.8	3.4
23	30*	22	4.80	23.00	105.51	19.2	2.8	8.0
23	30*	13	4.80	23.00	62.35	19.2	-6.2	38.0
			Sum	**868.00**	**3468.78**	**Mean**	**0.0**	
						Std. Dev	**4.0**	
						+2x(Std. Dev	**7.9**	
						-2x(Std. Dev)	**-7.9**	

Note: values in bold are outliers
* refers to assumed values

No. of Results: 37

k	4.00
Sum of Residual^2	**567.8**

BRIDGES IN JOHANNESBURG LOCALITY

Sheltered Grade 30-35 (N3 Between Heidelberg Road and Geldenhuis Interchanges)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\, t_i^{0.5}$	Predicted	Residual	Residual^2
22	35*	15	4.69	22.00	70.36	18.5	-3.5	12.5
23	35*	14	4.80	23.00	67.14	18.9	-4.9	24.5
23	35*	16	4.80	23.00	76.73	18.9	-2.9	8.7
23	35*	18	4.80	23.00	86.32	18.9	-0.9	0.9
23	35*	14	4.80	23.00	67.14	18.9	-4.9	24.5
23	35*	15	4.80	23.00	71.94	18.9	-3.9	15.6
23	35*	16	4.80	23.00	76.73	18.9	-2.9	8.7
23	35*	13	4.80	23.00	62.35	18.9	-5.9	35.4
23	35*	23	4.80	23.00	110.30	18.9	4.1	16.4
23	35*	21	4.80	23.00	100.71	18.9	2.1	4.2
23	35*	23	4.80	23.00	110.30	18.9	4.1	16.4
28	35*	19	5.29	28.00	100.54	20.9	-1.9	3.6
28	35*	20	5.29	28.00	105.83	20.9	-0.9	0.8
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.4
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.4
23	30*	13	4.80	23.00	62.35	18.9	-5.9	35.4
23	30*	17	4.80	23.00	81.53	18.9	-1.9	3.8
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.9
23	30*	20	4.80	23.00	95.92	18.9	1.1	1.1
23	30*	21	4.80	23.00	100.71	18.9	2.1	4.2
23	30*	24	4.80	23.00	115.10	18.9	5.1	25.5
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.9
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.9
23	30*	18	4.80	23.00	86.32	18.9	-0.9	0.9
23	30*	26	4.80	23.00	124.69	18.9	7.1	49.8
28	35*	22	5.29	28.00	116.41	20.9	1.1	1.2
28	35*	24	5.29	28.00	127.00	20.9	3.1	9.6
23	30*	23	4.80	23.00	110.30	18.9	4.1	16.4
23	35*	19	4.80	23.00	91.12	18.9	0.1	0.0
23	35*	22	4.80	23.00	105.51	18.9	3.1	9.3
23	30*	17	4.80	23.00	81.53	18.9	-1.9	3.8
23	30*	14	4.80	23.00	67.14	18.9	-4.9	24.5
22	30*	26	4.69	22.00	121.95	18.5	7.5	55.8
23	30*	21	4.80	23.00	100.71	18.9	2.1	4.2
23	30*	22	4.80	23.00	105.51	18.9	3.1	9.3
23	30*	13	4.80	23.00	62.35	18.9	-5.9	35.4
			Sum	**846.00**	**3342.14**	**Mean**	**0.0**	
						Std. Dev	**3.8**	
						+2x(Std. Dev	**7.5**	
						-2x(Std. Dev)	**-7.5**	

* refers to asumed value

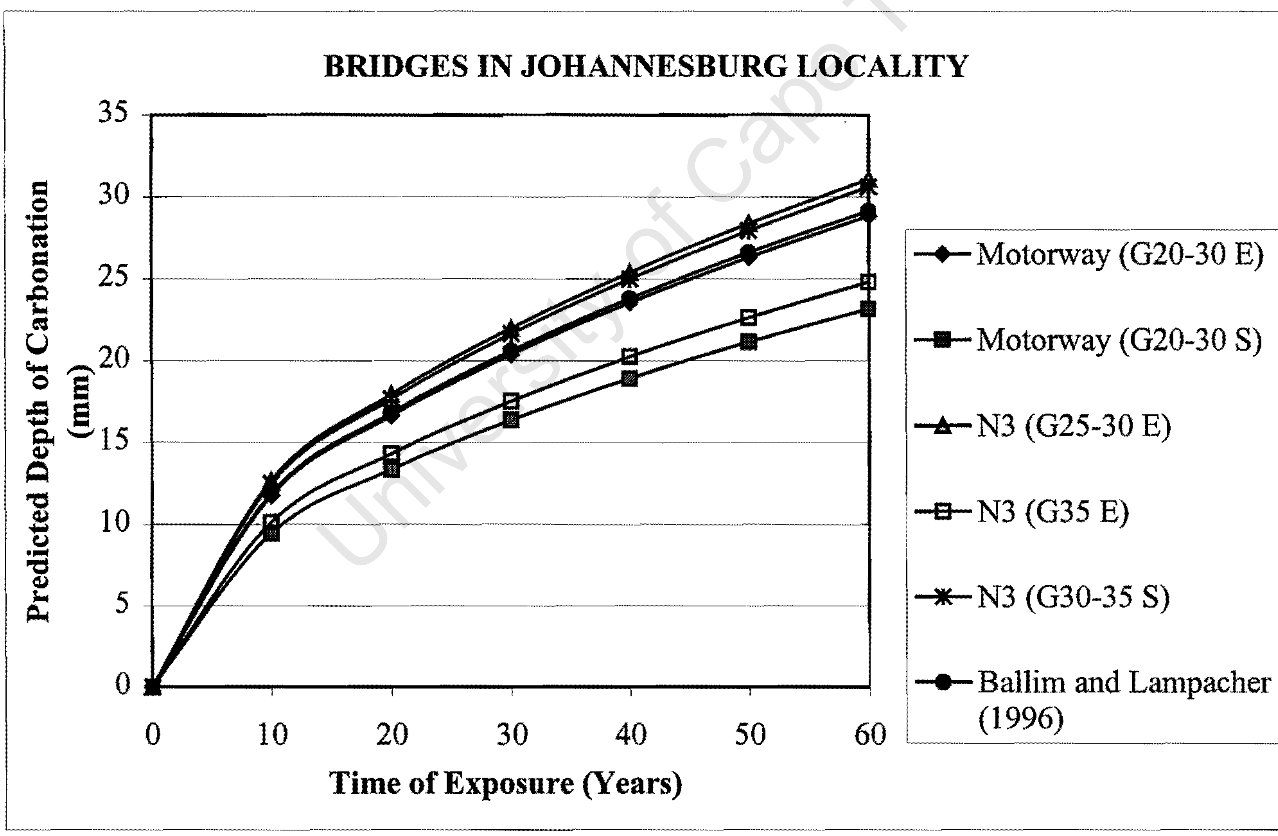
No. of Results: 36

k	3.95
Sum of Residual^2	**497.8**

BRIDGES IN JOHANNESBURG LOCALITY

Comparison of Carbonation Prediction Models

	Predicted Depth of Carbonation, d_c (mm)					
Time	Motorway	Motorway	N3	N3	N3	Ballim & Lam
	G20-30 E	G20-30 S	G25-30 E	G35 E	G 30-35 S	All Motorway
	$d_c = 3.72t^{0.5}$	$d_c = 2.99t^{0.5}$	$d_c = 4.01t^{0.5}$	$d_c = 3.20t^{0.5}$	$d_c = 3.95t^{0.5}$	$d_c = 3.76t^{0.5}$
0	0.0	0.0	0.0	0.0	0.0	0.0
10	11.8	9.5	12.7	10.1	12.5	11.9
20	16.6	13.4	17.9	14.3	17.7	16.8
30	20.4	16.4	22.0	17.5	21.6	20.6
40	23.5	18.9	25.4	20.2	25.0	23.8
50	26.3	21.1	28.4	22.6	27.9	26.6
60	28.8	23.2	31.1	24.8	30.6	29.1



JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20	15	5.48	30.00	82.16	21.2	-6.2	38.4
30	20	34	5.48	30.00	186.23	21.2	12.8	164.0
30	20	35	5.48	30.00	191.70	21.2	13.8	190.6
27	30	14	5.20	27.00	72.75	20.1	-6.1	37.3
27	30	10	5.20	27.00	51.96	20.1	-10.1	102.2
27	30	18	5.20	27.00	93.53	20.1	-2.1	4.4
27	**30**	**2**	**5.20**	**27.00**	**10.39**	**20.1**	**-18.1**	**327.9**
26	30	20	5.10	26.00	101.98	19.7	0.3	0.1
26	30	28	5.10	26.00	142.77	19.7	8.3	68.4
26	30	14	5.10	26.00	71.39	19.7	-5.7	32.8
26	30	10	5.10	26.00	50.99	19.7	-9.7	94.7
26	30	16	5.10	26.00	81.58	19.7	-3.7	13.9
26	30	15	5.10	26.00	76.49	19.7	-4.7	22.4
24	30	15	4.90	24.00	73.48	19.0	-4.0	15.7
24	**30**	**4**	**4.90**	**24.00**	**19.60**	**19.0**	**-15.0**	**223.7**
24	**30**	**3**	**4.90**	**24.00**	**14.70**	**19.0**	**-16.0**	**254.6**
24	30	20	4.90	24.00	97.98	19.0	1.0	1.1
24	30	30	4.90	24.00	146.97	19.0	11.0	121.9
24	**30**	**35**	**4.90**	**24.00**	**171.46**	**19.0**	**16.0**	**257.4**
24	30	20	4.90	24.00	97.98	19.0	1.0	1.1
24	30	20	4.90	24.00	97.98	19.0	1.0	1.1
21	30	13	4.58	21.00	59.57	17.7	-4.7	22.4
21	30	15	4.58	21.00	68.74	17.7	-2.7	7.5
20	30	8	4.47	20.00	35.78	17.3	-9.3	86.6
20	30	20	4.47	20.00	89.44	17.3	2.7	7.3
20	30	24	4.47	20.00	107.33	17.3	6.7	44.8
20	30	23	4.47	20.00	102.86	17.3	5.7	32.4
19	30	30	4.36	19.00	130.77	16.9	13.1	172.5
19	30	19	4.36	19.00	82.82	16.9	2.1	4.5
19	30	19	4.36	19.00	82.82	16.9	2.1	4.5
19	30	17	4.36	19.00	74.10	16.9	0.1	0.0
22	25	18	4.69	22.00	84.43	18.2	-0.2	0.0
22	25	19	4.69	22.00	89.12	18.2	0.8	0.7
23	25	21	4.80	23.00	100.71	18.6	2.4	6.0
23	25	17	4.80	23.00	81.53	18.6	-1.6	2.4
23	25	19	4.80	23.00	91.12	18.6	0.4	0.2
23	25	21	4.80	23.00	100.71	18.6	2.4	6.0
23	25	21	4.80	23.00	100.71	18.6	2.4	6.0
23	25	14	4.80	23.00	67.14	18.6	-4.6	20.8

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
23	25	11	4.80	23.00	52.75	18.6	-7.6	57.1
23	25	18	4.80	23.00	86.32	18.6	-0.6	0.3
23	25	10	4.80	23.00	47.96	18.6	-8.6	73.2
23	25	18	4.80	23.00	86.32	18.6	-0.6	0.3
23	25	24	4.80	23.00	115.10	18.6	5.4	29.6
28	25	16	5.29	28.00	84.66	20.5	-4.5	20.0
28	25	17	5.29	28.00	89.96	20.5	-3.5	12.1
23	25	15	4.80	23.00	71.94	18.6	-3.6	12.7
23	25	25	4.80	23.00	119.90	18.6	6.4	41.5
28	25	14	5.29	28.00	74.08	20.5	-6.5	41.9
28	25	17	5.29	28.00	89.96	20.5	-3.5	12.1
23	25	13	4.80	23.00	62.35	18.6	-5.6	30.9
23	30	23	4.80	23.00	110.30	18.6	4.4	19.7
23	30	18	4.80	23.00	86.32	18.6	-0.6	0.3
23	30	18	4.80	23.00	86.32	18.6	-0.6	0.3
23	30	26	4.80	23.00	124.69	18.6	7.4	55.4
23	30	25	4.80	23.00	119.90	18.6	6.4	41.5
23	30	24	4.80	23.00	115.10	18.6	5.4	29.6
23	30	24	4.80	23.00	115.10	18.6	5.4	29.6
23	30	22	4.80	23.00	105.51	18.6	3.4	11.8
28	30	30	5.29	28.00	158.75	20.5	9.5	90.7
28	30	26	5.29	28.00	137.58	20.5	5.5	30.5
28	30	31	5.29	28.00	164.04	20.5	10.5	110.7
28	30	23	5.29	28.00	121.70	20.5	2.5	6.4
23	30	11	4.80	23.00	52.75	18.6	-7.6	57.1
			Sum	**1541.00**	**5963.14**	**Mean**	**0.0**	
						Std. Dev	**7.1**	
						+2x(Std. Dev	**14.3**	
						-2x(Std. Dev)	**-14.3**	

No. of Results: 64

k	3.87

Sum of Residual^2	3213.7

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20	15	5.48	30.00	82.16	21.8	-6.8	46.6
30	**20**	**34**	**5.48**	**30.00**	**186.23**	**21.8**	**12.2**	**148.1**
30	**20**	**35**	**5.48**	**30.00**	**191.70**	**21.8**	**13.2**	**173.5**
27	30	14	5.20	27.00	72.75	20.7	-6.7	45.0
27	30	10	5.20	27.00	51.96	20.7	-10.7	114.7
27	30	18	5.20	27.00	93.53	20.7	-2.7	7.3
26	30	20	5.10	26.00	101.98	20.3	-0.3	0.1
26	30	28	5.10	26.00	142.77	20.3	7.7	59.0
26	30	14	5.10	26.00	71.39	20.3	-6.3	40.0
26	30	10	5.10	26.00	50.99	20.3	-10.3	106.5
26	30	16	5.10	26.00	81.58	20.3	-4.3	18.7
26	30	15	5.10	26.00	76.49	20.3	-5.3	28.3
24	30	15	4.90	24.00	73.48	19.5	-4.5	20.5
24	30	20	4.90	24.00	97.98	19.5	0.5	0.2
24	30	30	4.90	24.00	146.97	19.5	10.5	109.7
24	30	20	4.90	24.00	97.98	19.5	0.5	0.2
24	30	20	4.90	24.00	97.98	19.5	0.5	0.2
21	30	13	4.58	21.00	59.57	18.3	-5.3	27.7
21	30	15	4.58	21.00	68.74	18.3	-3.3	10.7
20	30	8	4.47	20.00	35.78	17.8	-9.8	96.5
20	30	20	4.47	20.00	89.44	17.8	2.2	4.7
20	30	24	4.47	20.00	107.33	17.8	6.2	38.2
20	30	23	4.47	20.00	102.86	17.8	5.2	26.8
19	**30**	**30**	**4.36**	**19.00**	**130.77**	**17.4**	**12.6**	**159.5**
19	30	19	4.36	19.00	82.82	17.4	1.6	2.7
19	30	19	4.36	19.00	82.82	17.4	1.6	2.7
19	30	17	4.36	19.00	74.10	17.4	-0.4	0.1
22	25	18	4.69	22.00	84.43	18.7	-0.7	0.5
22	25	19	4.69	22.00	89.12	18.7	0.3	0.1
23	25	21	4.80	23.00	100.71	19.1	1.9	3.6
23	25	17	4.80	23.00	81.53	19.1	-2.1	4.5
23	25	19	4.80	23.00	91.12	19.1	-0.1	0.0
23	25	21	4.80	23.00	100.71	19.1	1.9	3.6
23	25	21	4.80	23.00	100.71	19.1	1.9	3.6
23	25	14	4.80	23.00	67.14	19.1	-5.1	26.1
23	25	11	4.80	23.00	52.75	19.1	-8.1	65.8
23	25	18	4.80	23.00	86.32	19.1	-1.1	1.2
23	25	10	4.80	23.00	47.96	19.1	-9.1	83.1
23	25	18	4.80	23.00	86.32	19.1	-1.1	1.2

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 1st Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	$Residual^2$
23	25	24	4.80	23.00	115.10	19.1	4.9	23.9
28	25	16	5.29	28.00	84.66	21.1	-5.1	25.9
28	25	17	5.29	28.00	89.96	21.1	-4.1	16.7
23	25	15	4.80	23.00	71.94	19.1	-4.1	16.9
23	25	25	4.80	23.00	119.90	19.1	5.9	34.7
28	25	14	5.29	28.00	74.08	21.1	-7.1	50.3
28	25	17	5.29	28.00	89.96	21.1	-4.1	16.7
23	25	13	4.80	23.00	62.35	19.1	-6.1	37.4
23	30	23	4.80	23.00	110.30	19.1	3.9	15.1
23	30	18	4.80	23.00	86.32	19.1	-1.1	1.2
23	30	18	4.80	23.00	86.32	19.1	-1.1	1.2
23	30	26	4.80	23.00	124.69	19.1	6.9	47.4
23	30	25	4.80	23.00	119.90	19.1	5.9	34.7
23	30	24	4.80	23.00	115.10	19.1	4.9	23.9
23	30	24	4.80	23.00	115.10	19.1	4.9	23.9
23	30	22	4.80	23.00	105.51	19.1	2.9	8.3
28	30	30	5.29	28.00	158.75	21.1	8.9	79.4
28	30	26	5.29	28.00	137.58	21.1	4.9	24.1
28	30	31	5.29	28.00	164.04	21.1	9.9	98.2
28	30	23	5.29	28.00	121.70	21.1	1.9	3.7
23	30	11	4.80	23.00	52.75	19.1	-8.1	65.8
			Sum	**1442.00**	**5746.99**	**Mean**	**0.0**	
						Std. Dev	**6.0**	
						+2x(Std. Dev	**12.0**	
						-2x(Std. Dev)	**-12.0**	

No. of Results: 60

k	3.99

Sum of $Residual^2$	2130.8

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20	15	5.48	30.00	82.16	21.1	-6.1	36.6
27	30	14	5.20	27.00	72.75	20.0	-6.0	35.6
27	30	10	5.20	27.00	51.96	20.0	-10.0	99.4
27	30	18	5.20	27.00	93.53	20.0	-2.0	3.9
26	30	20	5.10	26.00	101.98	19.6	0.4	0.2
26	30	28	5.10	26.00	142.77	19.6	8.4	70.6
26	30	14	5.10	26.00	71.39	19.6	-5.6	31.3
26	30	10	5.10	26.00	50.99	19.6	-9.6	92.1
26	30	16	5.10	26.00	81.58	19.6	-3.6	12.9
26	30	15	5.10	26.00	76.49	19.6	-4.6	21.1
24	30	15	4.90	24.00	73.48	18.8	-3.8	14.7
24	30	20	4.90	24.00	97.98	18.8	1.2	1.4
24	**30**	**30**	**4.90**	**24.00**	**146.97**	**18.8**	**11.2**	**124.8**
24	30	20	4.90	24.00	97.98	18.8	1.2	1.4
24	30	20	4.90	24.00	97.98	18.8	1.2	1.4
21	30	13	4.58	21.00	59.57	17.6	-4.6	21.3
21	30	15	4.58	21.00	68.74	17.6	-2.6	6.8
20	30	8	4.47	20.00	35.78	17.2	-9.2	84.4
20	30	20	4.47	20.00	89.44	17.2	2.8	7.9
20	30	24	4.47	20.00	107.33	17.2	6.8	46.4
20	30	23	4.47	20.00	102.86	17.2	5.8	33.8
19	30	19	4.36	19.00	82.82	16.8	2.2	5.1
19	30	19	4.36	19.00	82.82	16.8	2.2	5.1
19	30	17	4.36	19.00	74.10	16.8	0.2	0.1
22	25	18	4.69	22.00	84.43	18.0	0.0	0.0
22	25	19	4.69	22.00	89.12	18.0	1.0	0.9
23	25	21	4.80	23.00	100.71	18.4	2.6	6.6
23	25	17	4.80	23.00	81.53	18.4	-1.4	2.0
23	25	19	4.80	23.00	91.12	18.4	0.6	0.3
23	25	21	4.80	23.00	100.71	18.4	2.6	6.6
23	25	21	4.80	23.00	100.71	18.4	2.6	6.6
23	25	14	4.80	23.00	67.14	18.4	-4.4	19.6
23	25	11	4.80	23.00	52.75	18.4	-7.4	55.2
23	25	18	4.80	23.00	86.32	18.4	-0.4	0.2
23	25	10	4.80	23.00	47.96	18.4	-8.4	71.1
23	25	18	4.80	23.00	86.32	18.4	-0.4	0.2
23	25	24	4.80	23.00	115.10	18.4	5.6	31.0
28	25	16	5.29	28.00	84.66	20.3	-4.3	18.8
28	25	17	5.29	28.00	89.96	20.3	-3.3	11.1

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 2nd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
23	25	15	4.80	23.00	71.94	18.4	-3.4	11.8
23	25	25	4.80	23.00	119.90	18.4	6.6	43.1
28	25	14	5.29	28.00	74.08	20.3	-6.3	40.1
28	25	17	5.29	28.00	89.96	20.3	-3.3	11.1
23	25	13	4.80	23.00	62.35	18.4	-5.4	29.5
23	30	23	4.80	23.00	110.30	18.4	4.6	20.9
23	30	18	4.80	23.00	86.32	18.4	-0.4	0.2
23	30	18	4.80	23.00	86.32	18.4	-0.4	0.2
23	30	26	4.80	23.00	124.69	18.4	7.6	57.3
23	30	25	4.80	23.00	119.90	18.4	6.6	43.1
23	30	24	4.80	23.00	115.10	18.4	5.6	31.0
23	30	24	4.80	23.00	115.10	18.4	5.6	31.0
23	30	22	4.80	23.00	105.51	18.4	3.6	12.7
28	30	30	5.29	28.00	158.75	20.3	9.7	93.4
28	30	26	5.29	28.00	137.58	20.3	5.7	32.1
28	30	31	5.29	28.00	164.04	20.3	10.7	113.7
28	30	23	5.29	28.00	121.70	20.3	2.7	7.1
23	30	11	4.80	23.00	52.75	18.4	-7.4	55.2
			Sum	**1363.00**	**5238.29**	**Mean**	**0.0**	
						Std. Dev	**5.4**	
						+2x(Std. Dev	**10.8**	
						-2x(Std. Dev)	**-10.8**	

No. of Results: 57

k	3.84

Sum of Residual^2	1622.2

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 3rd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20	15	5.48	30.00	82.16	20.8	-5.8	33.9
27	30	14	5.20	27.00	72.75	19.8	-5.8	33.1
27	30	10	5.20	27.00	51.96	19.8	-9.8	95.2
27	30	18	5.20	27.00	93.53	19.8	-1.8	3.1
26	30	20	5.10	26.00	101.98	19.4	0.6	0.4
26	30	28	5.10	26.00	142.77	19.4	8.6	74.2
26	30	14	5.10	26.00	71.39	19.4	-5.4	29.0
26	30	10	5.10	26.00	50.99	19.4	-9.4	88.1
26	30	16	5.10	26.00	81.58	19.4	-3.4	11.5
26	30	15	5.10	26.00	76.49	19.4	-4.4	19.3
24	30	15	4.90	24.00	73.48	18.6	-3.6	13.2
24	30	20	4.90	24.00	97.98	18.6	1.4	1.9
24	30	20	4.90	24.00	97.98	18.6	1.4	1.9
24	30	20	4.90	24.00	97.98	18.6	1.4	1.9
21	30	13	4.58	21.00	59.57	17.4	-4.4	19.6
21	30	15	4.58	21.00	68.74	17.4	-2.4	5.9
20	30	8	4.47	20.00	35.78	17.0	-9.0	81.1
20	30	20	4.47	20.00	89.44	17.0	3.0	9.0
20	30	24	4.47	20.00	107.33	17.0	7.0	48.9
20	30	23	4.47	20.00	102.86	17.0	6.0	35.9
19	30	19	4.36	19.00	82.82	16.6	2.4	5.9
19	30	19	4.36	19.00	82.82	16.6	2.4	5.9
19	30	17	4.36	19.00	74.10	16.6	0.4	0.2
22	25	18	4.69	22.00	84.43	17.8	0.2	0.0
22	25	19	4.69	22.00	89.12	17.8	1.2	1.4
23	25	21	4.80	23.00	100.71	18.2	2.8	7.6
23	25	17	4.80	23.00	81.53	18.2	-1.2	1.5
23	25	19	4.80	23.00	91.12	18.2	0.8	0.6
23	25	21	4.80	23.00	100.71	18.2	2.8	7.6
23	25	21	4.80	23.00	100.71	18.2	2.8	7.6
23	25	14	4.80	23.00	67.14	18.2	-4.2	17.9
23	25	11	4.80	23.00	52.75	18.2	-7.2	52.4
23	25	18	4.80	23.00	86.32	18.2	-0.2	0.1
23	25	10	4.80	23.00	47.96	18.2	-8.2	67.8
23	25	18	4.80	23.00	86.32	18.2	-0.2	0.1
23	25	24	4.80	23.00	115.10	18.2	5.8	33.2
28	25	16	5.29	28.00	84.66	20.1	-4.1	17.0
28	25	17	5.29	28.00	89.96	20.1	-3.1	9.7
23	25	15	4.80	23.00	71.94	18.2	-3.2	10.5

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 3rd Elimination of Gross Outliers)

n	0.5

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
23	25	25	4.80	23.00	119.90	18.2	6.8	45.8
28	25	14	5.29	28.00	74.08	20.1	-6.1	37.5
28	25	17	5.29	28.00	89.96	20.1	-3.1	9.7
23	25	13	4.80	23.00	62.35	18.2	-5.2	27.4
23	30	23	4.80	23.00	110.30	18.2	4.8	22.7
23	30	18	4.80	23.00	86.32	18.2	-0.2	0.1
23	30	18	4.80	23.00	86.32	18.2	-0.2	0.1
23	30	26	4.80	23.00	124.69	18.2	7.8	60.3
23	30	25	4.80	23.00	119.90	18.2	6.8	45.8
23	30	24	4.80	23.00	115.10	18.2	5.8	33.2
23	30	24	4.80	23.00	115.10	18.2	5.8	33.2
23	30	22	4.80	23.00	105.51	18.2	3.8	14.2
28	30	30	5.29	28.00	158.75	20.1	9.9	97.6
28	30	26	5.29	28.00	137.58	20.1	5.9	34.6
28	**30**	**31**	**5.29**	**28.00**	**164.04**	**20.1**	**10.9**	**118.4**
28	30	23	5.29	28.00	121.70	20.1	2.9	8.3
23	30	11	4.80	23.00	52.75	18.2	-7.2	52.4
			Sum	**1339.00**	**5091.32**	**Mean**	**0.0**	
						Std. Dev	**5.2**	
						+2x(Std. Dev	**10.4**	
						-2x(Std. Dev)	**-10.4**	

No. of Results: 56

k	3.80

Sum of Residual^2	1495.1

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 4th Elimination of Gross Outliers)

n	0.5

dc = kt0.5

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
30	20	15	5.48	30.00	82.16	20.6	-5.6	31.2
27	30	14	5.20	27.00	72.75	19.5	-5.5	30.6
27	30	10	5.20	27.00	51.96	19.5	-9.5	90.8
27	30	18	5.20	27.00	93.53	19.5	-1.5	2.3
26	30	20	5.10	26.00	101.98	19.2	0.8	0.7
26	30	28	5.10	26.00	142.77	19.2	8.8	78.1
26	30	14	5.10	26.00	71.39	19.2	-5.2	26.7
26	30	10	5.10	26.00	50.99	19.2	-9.2	84.0
26	30	16	5.10	26.00	81.58	19.2	-3.2	10.0
26	30	15	5.10	26.00	76.49	19.2	-4.2	17.3
24	30	15	4.90	24.00	73.48	18.4	-3.4	11.6
24	30	20	4.90	24.00	97.98	18.4	1.6	2.5
24	30	20	4.90	24.00	97.98	18.4	1.6	2.5
24	30	20	4.90	24.00	97.98	18.4	1.6	2.5
21	30	13	4.58	21.00	59.57	17.2	-4.2	17.8
21	30	15	4.58	21.00	68.74	17.2	-2.2	4.9
20	30	8	4.47	20.00	35.78	16.8	-8.8	77.6
20	30	20	4.47	20.00	89.44	16.8	3.2	10.2
20	30	24	4.47	20.00	107.33	16.8	7.2	51.7
20	30	23	4.47	20.00	102.86	16.8	6.2	38.3
19	30	19	4.36	19.00	82.82	16.4	2.6	6.9
19	30	19	4.36	19.00	82.82	16.4	2.6	6.9
19	30	17	4.36	19.00	74.10	16.4	0.6	0.4
22	25	18	4.69	22.00	84.43	17.6	0.4	0.1
22	25	19	4.69	22.00	89.12	17.6	1.4	1.9
23	25	21	4.80	23.00	100.71	18.0	3.0	8.9
23	25	17	4.80	23.00	81.53	18.0	-1.0	1.1
23	25	19	4.80	23.00	91.12	18.0	1.0	1.0
23	25	21	4.80	23.00	100.71	18.0	3.0	8.9
23	25	21	4.80	23.00	100.71	18.0	3.0	8.9
23	25	14	4.80	23.00	67.14	18.0	-4.0	16.2
23	25	11	4.80	23.00	52.75	18.0	-7.0	49.3
23	25	18	4.80	23.00	86.32	18.0	0.0	0.0
23	25	10	4.80	23.00	47.96	18.0	-8.0	64.4
23	25	18	4.80	23.00	86.32	18.0	0.0	0.0
23	25	24	4.80	23.00	115.10	18.0	6.0	35.7
28	25	16	5.29	28.00	84.66	19.9	-3.9	15.1
28	25	17	5.29	28.00	89.96	19.9	-2.9	8.3
23	25	15	4.80	23.00	71.94	18.0	-3.0	9.1

JOHANNESBURG LOCALITY

Combine: Data of Exposed Elements of Motorway System (MS) and N3 (Continued)

Grade 20 - 30 (MS (Grade 20-30 E) and N3 (Grade 25-30 E)

Method of Analysis: Method of Least Squares
(After the 4th Elimination of Gross Outliers)

n	**0.5**

$d_c = kt^{0.5}$

Age (t)	Grade	d_c	$t^{0.5}$	$t^{1.0}$	$d_{ci}\ t_i^{0.5}$	Predicted	Residual	Residual^2
23	25	25	4.80	23.00	119.90	18.0	7.0	48.7
28	25	14	5.29	28.00	74.08	19.9	-5.9	34.7
28	25	17	5.29	28.00	89.96	19.9	-2.9	8.3
23	25	13	4.80	23.00	62.35	18.0	-5.0	25.2
23	30	23	4.80	23.00	110.30	18.0	5.0	24.8
23	30	18	4.80	23.00	86.32	18.0	0.0	0.0
23	30	18	4.80	23.00	86.32	18.0	0.0	0.0
23	30	26	4.80	23.00	124.69	18.0	8.0	63.6
23	30	25	4.80	23.00	119.90	18.0	7.0	48.7
23	30	24	4.80	23.00	115.10	18.0	6.0	35.7
23	30	24	4.80	23.00	115.10	18.0	6.0	35.7
23	30	22	4.80	23.00	105.51	18.0	4.0	15.8
28	30	30	5.29	28.00	158.75	19.9	10.1	102.3
28	30	26	5.29	28.00	137.58	19.9	6.1	37.4
28	30	23	5.29	28.00	121.70	19.9	3.1	9.7
23	30	11	4.80	23.00	52.75	18.0	-7.0	49.3
			Sum	**1311.00**	**4927.29**	**Mean**	**0.1**	
						Std. Dev	**5.0**	
						+2x(Std. Dev	**10.1**	
						-2x(Std. Dev)	**-10.1**	

Note: Values in bold are outliers
All strengths are assumed strengths

No. of Results: 55

k	**3.76**

Sum of Residual^2	**1374.2**

APPENDIX G

COMPUTATION OF PERCENTILE CARBONATION DEPTH VALUES FOR THE LOCALITIES

G1. Cape Peninsula Locality

G2. Durban Locality

G3. Johannesburg Locality

G1. CAPE PENINSULA LOCALITY

The Percentile Carbonation Depth Value

Grade 20 (Exposed elements with compressive strengths: 21-30 MPa at 28 days)

Age (t) (Years)	Grade (MPa)	d_c (mm)	k ($mm/year^{0.4}$)	k (ranked) ($mm/year^{0.4}$)	Rank	Probability (P<d)	NormDist
33	27.7*	17	4.20	1.53	1	0.06	0.10
33	27.7	10	2.47	1.75	2	0.12	0.12
40	30*	23	5.26	1.93	3	0.18	0.15
42	23.1	27	6.05	2.12	4	0.24	0.18
42	30	26	5.83	2.14	5	0.29	0.18
45	26.1	25	5.45	2.31	6	0.35	0.21
45	30*	8	1.75	2.47	7	0.41	0.24
45	30*	7	1.53	3.53	8	0.47	0.49
47	22.5	9	1.93	3.86	9	0.53	0.57
47	30*	18	3.86	4.09	10	0.59	0.63
47	30*	10	2.14	4.20	11	0.65	0.66
47	30*	21	4.50	4.50	12	0.71	0.73
67	30*	19	3.53	5.26	13	0.76	0.86
67	30*	22	4.09	5.45	14	0.82	0.89
75	30*	13	2.31	5.83	15	0.88	0.93
76	30*	12	2.12	6.05	16	0.94	0.94
			Average	**3.56**			
			Std. Dev.	**1.56**			

* refers to assumed value

Grade 40 (Exposed elements with compressive strengths: 41-50 MPa at 28 days)

Age (t) (Years)	Grade (MPa)	d_c (mm)	k ($mm/year^{0.4}$)	k (ranked) ($mm/year^{0.4}$)	Rank	Probability (P<d)	NormDist
15	49.4	7	2.37	1.21	1	0.06	0.07
15	49.4*	7	2.37	1.29	2	0.11	0.09
16	42.5	4	1.32	1.32	3	0.17	0.10
17	46.38	8	2.58	1.51	4	0.22	0.16
17	46.38*	7	2.25	1.58	5	0.28	0.20
17	43.8*	5	1.61	1.61	6	0.33	0.21
17	43.8	4	1.29	1.98	7	0.39	0.40
17	43.3	9	2.90	2.22	8	0.44	0.56
17	43.3	10	3.22	2.25	9	0.50	0.57
20	44.4*	4	1.21	2.32	10	0.56	0.62
20	44.4	5	1.51	2.32	11	0.61	0.62
22	45*	8	2.32	2.37	12	0.67	0.64
22	45	8	2.32	2.37	13	0.72	0.64
33	40.5	8	1.98	2.58	14	0.78	0.76
33	40.5	9	2.22	2.90	15	0.83	0.88
33	48.8	13	3.21	3.21	16	0.89	0.95
41	41.6	7	1.58	3.22	17	0.94	0.96
			Average	**2.13**			
			Std. Dev.	**0.64**			

* refers to assumed value

G1. CAPE PENINSULA LOCALITY

The Percentile Carbonation Depth Value

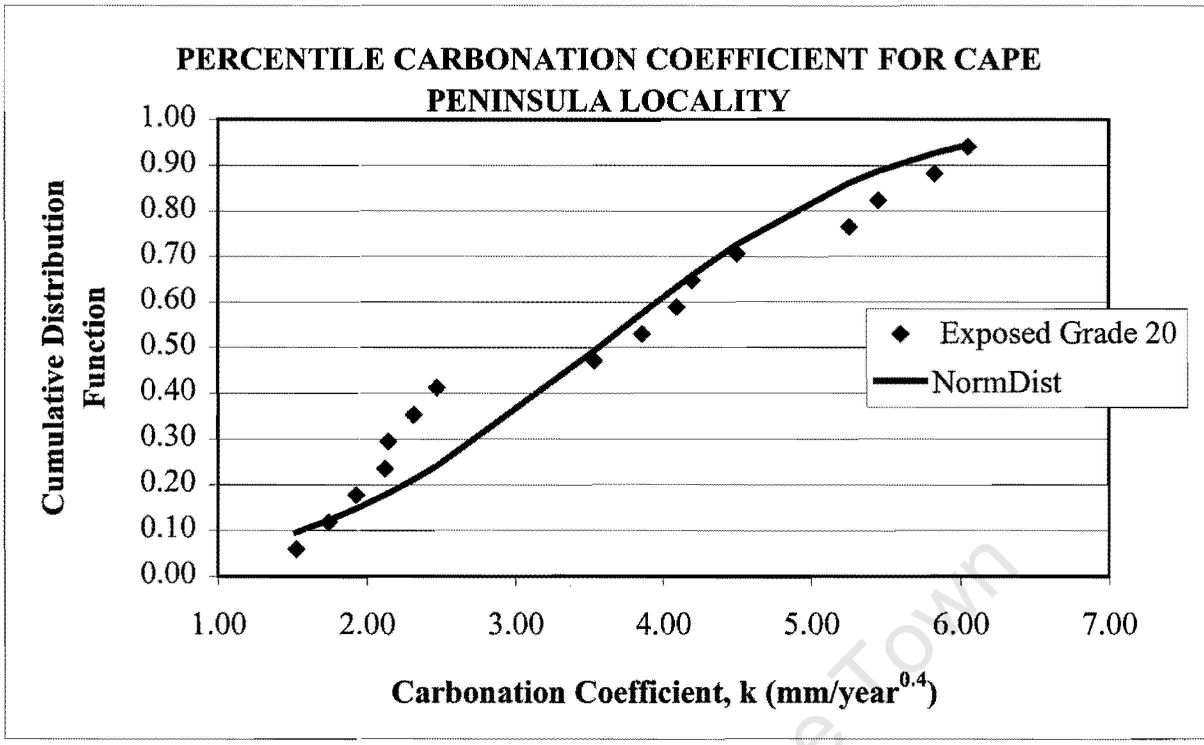
Grade 30 (Exposed elements with compressive strengths: 31-40 MPa at 28 days)

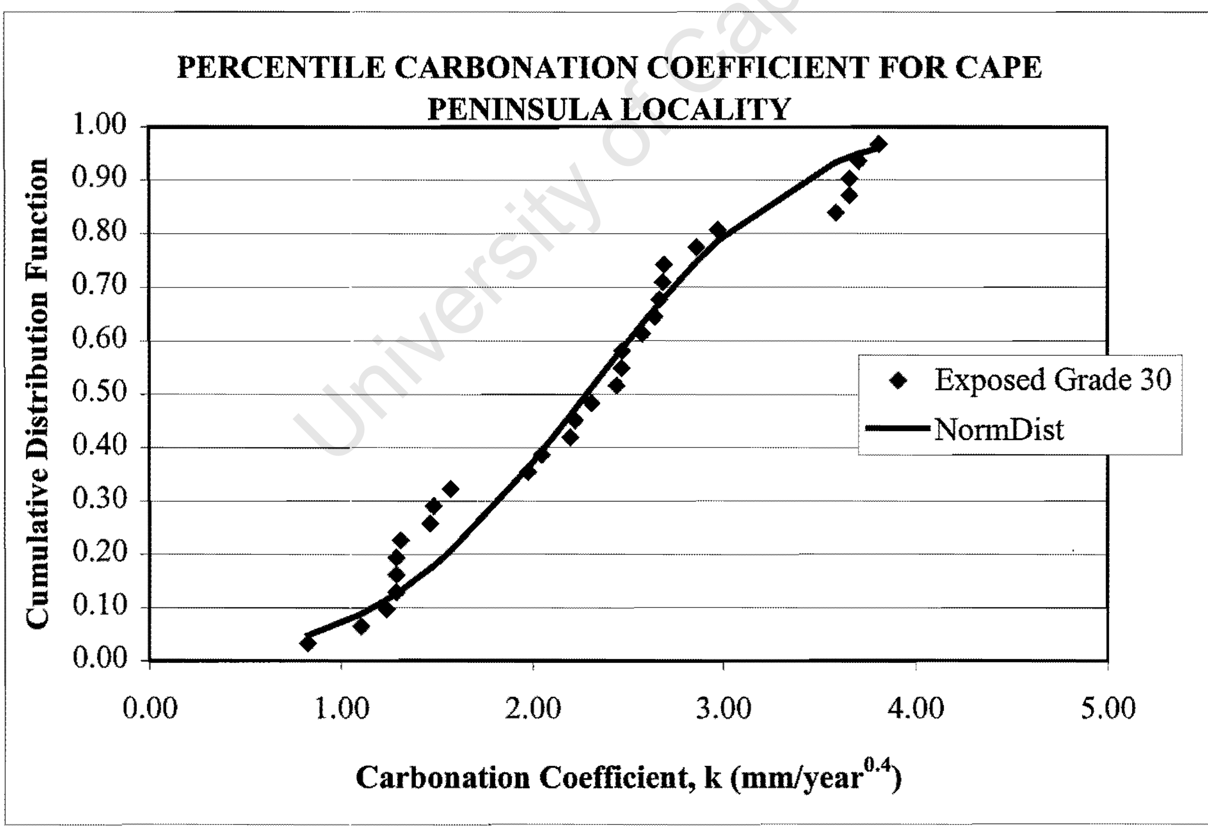
Age (t)	Grade	d_c	k	k (ranked)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.4}$)	(mm/year$^{0.4}$)		(P<d)	
33	39.4	8	1.98	0.83	1	0.03	0.05
33	32.2	10	2.47	1.10	2	0.06	0.09
33	39.2*	5	1.23	1.23	3	0.10	0.11
33	39.2	6	1.48	1.29	4	0.13	0.13
33	39.2	9	2.22	1.29	5	0.16	0.13
17	34*	4	1.29	1.29	6	0.19	0.13
17	34	8	2.58	1.31	7	0.23	0.13
17	40*	4	1.29	1.46	8	0.26	0.17
17	40*	4	1.29	1.48	9	0.29	0.18
34	36.1	9	2.20	1.57	10	0.32	0.21
34	36.1*	10	2.44	1.98	11	0.35	0.36
34	38.3	11	2.68	2.05	12	0.39	0.39
34	38.3*	15	3.66	2.20	13	0.42	0.46
34	35*	6	1.46	2.22	14	0.45	0.47
40	40*	13	2.97	2.31	15	0.48	0.51
40	36.9	16	3.66	2.44	16	0.52	0.57
42	30.8	16	3.59	2.47	17	0.55	0.58
43	39.4	12	2.67	2.47	18	0.58	0.58
45	38.3	6	1.31	2.58	19	0.61	0.63
45	38.3*	17	3.71	2.64	20	0.65	0.66
67	31.1	11	2.05	2.67	21	0.68	0.67
42	33.3	12	2.69	2.68	22	0.71	0.68
42	33.3*	17	3.81	2.69	23	0.74	0.68
42	36.9	7	1.57	2.86	24	0.77	0.75
42	36.9*	11	2.47	2.97	25	0.81	0.79
16	32.2	7	2.31	3.59	26	0.84	0.93
25	35.6*	4	1.10	3.66	27	0.87	0.94
25	35.6	3	0.83	3.66	28	0.90	0.94
44	30.8*	12	2.64	3.71	29	0.94	0.95
44	30.8	13	2.86	3.81	30	0.97	0.96
			Average	**2.28**			
			Std. Dev.	**0.87**			

* refers to assumed value

G1. CAPE PENINSULA LOCALITY

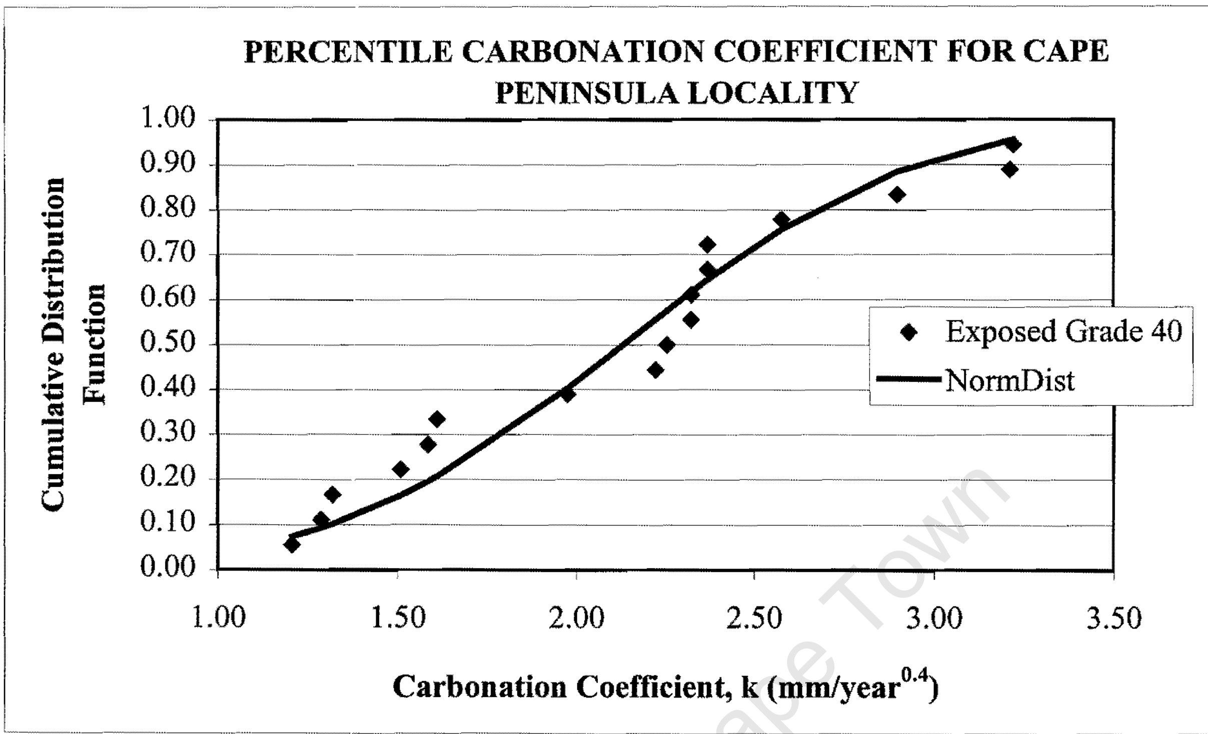
Percentile Carbonation Coefficient (k) for Exposed 20 and 30 Concretes





G1. CAPE PENINSULA LOCALITY

Percentile Carbonation Coefficient (k) for Exposed Grade 40 Concretes



G1. CAPE PENINSULA LOCALITY

Selected Percentile Carbonation Depth Value

1. Exposed Grade 20 Concrete

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 1.53)	(k = 2.25)	(k = 3.56)	(k = 4.91)	(k = 5.56)
0	0	0	0	0	0
10	4	6	9	12	14
20	5	7	12	16	18
30	6	9	14	19	22
40	7	10	16	21	24
50	7	11	17	23	27
60	8	12	18	25	29

2. Exposed Grade 30 Concrete

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 1.16)	(k = 1.55)	(k = 2.27)	(k = 3.02)	(k = 3.45)
0	0	0	0	0	0
10	3	4	6	8	9
20	4	5	8	10	11
30	5	6	9	12	13
40	5	7	10	13	15
50	6	7	11	14	16
60	6	8	12	16	18

3. Exposed Grade 40 Concrete

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 1.31)	(k = 1.59)	(k = 2.13)	(k = 2.69)	(k = 2.95)
0	0	0	0	0	0
10	3	4	5	7	7
20	4	5	7	9	10
30	5	6	8	10	11
40	6	7	9	12	13
50	6	8	10	13	14
60	7	8	11	14	15

G2. DURBAN LOCALITY

The Percentile Carbonation Depth Value

Grade 20-25 (Combined Exposed and Sheltered Elements between 1956 - 1964)

Age (t)	Grade	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.4}$)	(mm/year$^{0.4}$)		(P<d)	
37	20	9	2.12	1.63	1	0.03	0.05
37	20	13	3.07	1.75	2	0.06	0.06
38	20	18	4.20	1.76	3	0.09	0.06
38	20	12	2.80	1.96	4	0.11	0.10
38	20	7	1.63	1.98	5	0.14	0.10
44	20	14	3.08	2.12	6	0.17	0.14
44	20	20	4.40	2.18	7	0.20	0.15
45	20	9	1.96	2.20	8	0.23	0.16
45	20	14	3.05	2.40	9	0.26	0.22
45	20	8	1.75	2.52	10	0.29	0.26
40	20	16	3.66	2.62	11	0.31	0.30
40	20	20	4.57	2.64	12	0.34	0.31
40	20	16	3.66	2.80	13	0.37	0.38
45	20	12	2.62	2.80	14	0.40	0.38
45	20	10	2.18	3.05	15	0.43	0.49
44	20	10	2.20	3.05	16	0.46	0.49
44	20	19	4.18	3.07	17	0.49	0.50
44	20	14	3.08	3.08	18	0.51	0.50
44	20	12	2.64	3.08	19	0.54	0.50
44	20	15	3.30	3.08	20	0.57	0.50
44	20	21	4.62	3.08	21	0.60	0.50
37	20*	18	4.25	3.27	22	0.63	0.59
38	20	12	2.80	3.30	23	0.66	0.60
38	20	14	3.27	3.66	24	0.69	0.75
44	20	9	1.98	3.66	25	0.71	0.75
44	20	8	1.76	3.74	26	0.74	0.78
45	20	14	3.05	3.89	27	0.77	0.83
40	20	17	3.89	3.93	28	0.80	0.84
40	20	11	2.52	4.18	29	0.83	0.90
45	20*	11	2.40	4.20	30	0.86	0.90
45	20*	18	3.93	4.25	31	0.89	0.91
44	20*	17	3.74	4.40	32	0.91	0.94
44	20*	14	3.08	4.57	33	0.94	0.96
44	20	14	3.08	4.62	34	0.97	0.96
			Average	**3.07**			
			Std. Dev.	**0.86**			

* refers to assumed value

G2. DURBAN LOCALITY

The Percentile Carbonation Depth Value

Grade 20-25 (Combined Exposed and Sheltered Elements between 1970 - 1982)

Age (t) (Years)	Grade (MPa)	d_c (mm)	k (mm/year$^{0.4}$)	k (sorted) (mm/year$^{0.4}$)	Rank	Probability (P<d)	NormDist
19	25	27	8.32	1.40	1	0.02	0.01
19	25	18	5.54	2.05	2	0.03	0.04
21	20	17	5.03	2.28	3	0.05	0.05
21	25	26	7.69	2.52	4	0.06	0.07
24	25	25	7.01	2.60	5	0.08	0.07
24	25	26	7.29	2.80	6	0.09	0.09
25	25	18	4.97	2.85	7	0.11	0.10
25	25	21	5.79	2.86	8	0.12	0.10
25	25	22	6.07	2.86	9	0.14	0.10
25	25	23	6.35	3.08	10	0.15	0.12
25	25	14	3.86	3.12	11	0.17	0.13
25	25	20	5.52	3.12	12	0.18	0.13
25	25	12	3.31	3.12	13	0.20	0.13
25	25	16	4.42	3.16	14	0.22	0.14
25	25	22	6.07	3.26	15	0.23	0.15
26	25	16	4.35	3.31	16	0.25	0.16
26	25	12	3.26	3.42	17	0.26	0.17
28	25	12	3.16	3.43	18	0.28	0.17
28	25	15	3.96	3.86	19	0.29	0.25
29	20	12	3.12	3.90	20	0.31	0.26
29	25	11	2.86	3.96	21	0.32	0.27
29	20	12	3.12	4.16	22	0.34	0.31
29	20	23	5.98	4.28	23	0.35	0.34
29	25	16	4.16	4.35	24	0.37	0.35
29	20	19	4.94	4.42	25	0.38	0.37
23	25	25	7.13	4.85	26	0.40	0.47
23	25	22	6.28	4.87	27	0.42	0.48
23	25	23	6.56	4.94	28	0.43	0.49
23	25	20	5.71	4.97	29	0.45	0.50
23	25	15	4.28	5.03	30	0.46	0.52
23	25	24	6.85	5.05	31	0.48	0.52
23	25	19	5.42	5.14	32	0.49	0.54
23	25	22	6.28	5.24	33	0.51	0.57
23	25	24	6.85	5.24	34	0.52	0.57
23	25	18	5.14	5.42	35	0.54	0.61
23	25	8	2.28	5.43	36	0.55	0.61
23	25	10	2.85	5.52	37	0.57	0.63
24	25	9	2.52	5.54	38	0.58	0.64
24	25	10	2.80	5.71	39	0.60	0.68
30	25	12	3.08	5.71	40	0.62	0.68
19	25	17	5.24	5.79	41	0.63	0.69

G2. DURBAN LOCALITY

The Percentile Carbonation Depth Value

Grade 20-25 (Combined Exposed and Sheltered Elements between 1970 - 1982) (Continued)

Age (t)	Grade	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.4}$)	(mm/year$^{0.4}$)		(P<d)	
21	25	21	6.21	5.79	42	0.65	0.69
24	25	18	5.05	5.89	43	0.66	0.71
24	25	24	6.73	5.98	44	0.68	0.73
25	25	24	6.62	6.07	45	0.69	0.75
25	25	19	5.24	6.07	46	0.71	0.75
25	25	22	6.07	6.07	47	0.72	0.75
25	25	28	7.73	6.21	48	0.74	0.78
25	25	21	5.79	6.28	49	0.75	0.79
25	25	24	6.62	6.28	50	0.77	0.79
26	25	20	5.43	6.35	51	0.78	0.80
28	25	13	3.43	6.56	52	0.80	0.84
29	25	11	2.86	6.56	53	0.82	0.84
29	20	10	2.60	6.62	54	0.83	0.85
29	25	12	3.12	6.62	55	0.85	0.85
29	20	15	3.90	6.73	56	0.86	0.86
23	25	23	6.56	6.85	57	0.88	0.88
23	25	17	4.85	6.85	58	0.89	0.88
23	25	20	5.71	7.01	59	0.91	0.90
23	25	12	3.42	7.13	60	0.92	0.91
24	25	21	5.89	7.29	61	0.94	0.92
24	25	5	1.40	7.69	62	0.95	0.95
30	25	8	2.05	7.73	63	0.97	0.95
30	25	19	4.87	8.32	64	0.98	0.98
			Average	**4.96**			
			Std. Dev.	**1.63**			

* refers to assumed value

G2. DURBAN LOCALITY

The Percentile Carbonation Depth Value

Grade 30-35 (Combined Exposed and Sheltered Elements between 1970 - 1982)

Age (t) (Years)	Grade (MPa)	d_c (mm)	k (mm/year$^{0.4}$)	k (sorted) (mm/year$^{0.4}$)	Rank	Probability (P<d)	NormDist
21	30	10	2.96	0.57	1	0.03	0.02
25	30	5	1.38	0.64	2	0.06	0.03
25	30	12	3.31	0.86	3	0.09	0.04
25	30	13	3.59	1.38	4	0.13	0.07
26	30	16	4.35	2.00	5	0.16	0.15
28	30	21	5.54	2.25	6	0.19	0.19
28	30	18	4.75	2.25	7	0.22	0.19
28	30	15	3.96	2.57	8	0.25	0.25
28	30	22	5.80	2.96	9	0.28	0.33
17	35	12	3.86	3.04	10	0.31	0.35
17	30	20	6.44	3.31	11	0.34	0.42
17	30	2	0.64	3.42	12	0.38	0.45
17	35	12	3.86	3.42	13	0.41	0.45
17	30	14	4.51	3.59	14	0.44	0.49
17	30	7	2.25	3.71	15	0.47	0.52
23	30	13	3.71	3.86	16	0.50	0.56
23	30	22	6.28	3.86	17	0.53	0.56
23	30	14	3.99	3.96	18	0.56	0.59
23	30	2	0.57	3.96	19	0.59	0.59
30	30	10	2.57	3.99	20	0.63	0.60
19	30	16	4.93	4.19	21	0.66	0.64
21	30	18	5.33	4.35	22	0.69	0.68
25	30	11	3.04	4.48	23	0.72	0.71
28	30	15	3.96	4.51	24	0.75	0.72
28	30	17	4.48	4.75	25	0.78	0.77
17	30	7	2.25	4.93	26	0.81	0.80
17	30	13	4.19	5.33	27	0.84	0.87
23	30	7	2.00	5.54	28	0.88	0.89
23	30	3	0.86	5.80	29	0.91	0.92
23	30	12	3.42	6.28	30	0.94	0.96
23	30	12	3.42	6.44	31	0.97	0.97
			Average	**3.62**			
			Std. Dev.	**1.54**			

G2. DURBAN LOCALITY

The Percentile Carbonation Depth Value

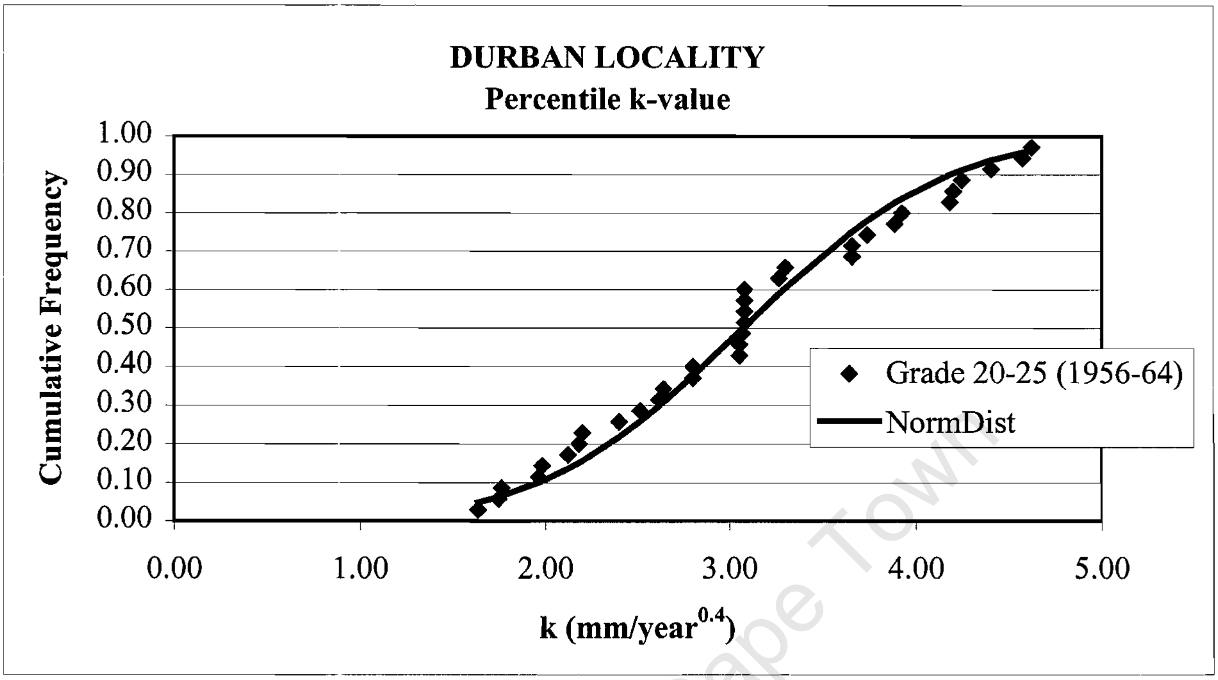
Grade 40-45 (Sheltered Elements between 1970 - 1982)

Age (t)	Grade	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.4}$)	(mm/year$^{0.4}$)		(P<d)	
25	40	7	1.93	0.81	1	0.08	0.08
25	40	18	4.97	1.29	2	0.17	0.15
25	40	15	4.14	1.71	3	0.25	0.24
26	40	3	0.81	1.85	4	0.33	0.27
28	40	7	1.85	1.93	5	0.42	0.29
17	45	11	3.54	2.28	6	0.50	0.39
17	45	4	1.29	2.85	7	0.58	0.56
23	40	10	2.85	3.54	8	0.67	0.75
23	40	13	3.71	3.71	9	0.75	0.79
23	40	6	1.71	4.14	10	0.83	0.87
23	40	8	2.28	4.97	11	0.92	0.96
			Average	**2.64**			
			Std. Dev.	**1.30**			

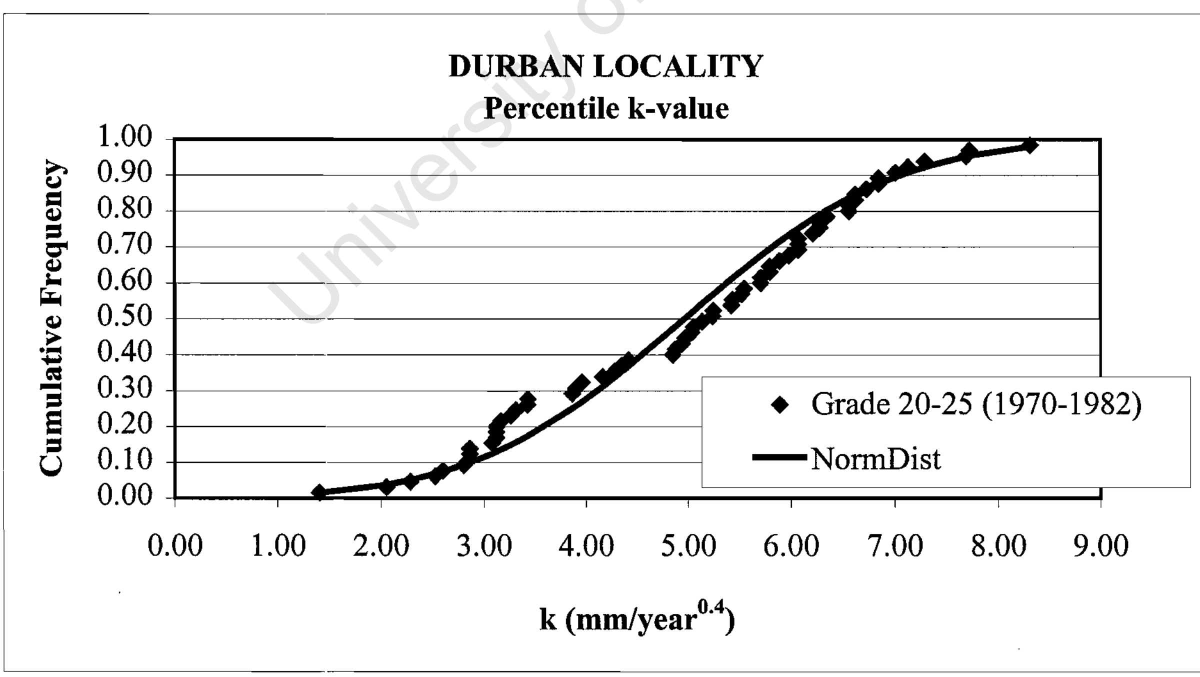
G2. DURBAN LOCALITY

Percentile Carbonation Coefficient (k) Values

1. Grade 20-25 (Combined Exposed and Sheltered Elements between 1956 - 1964)



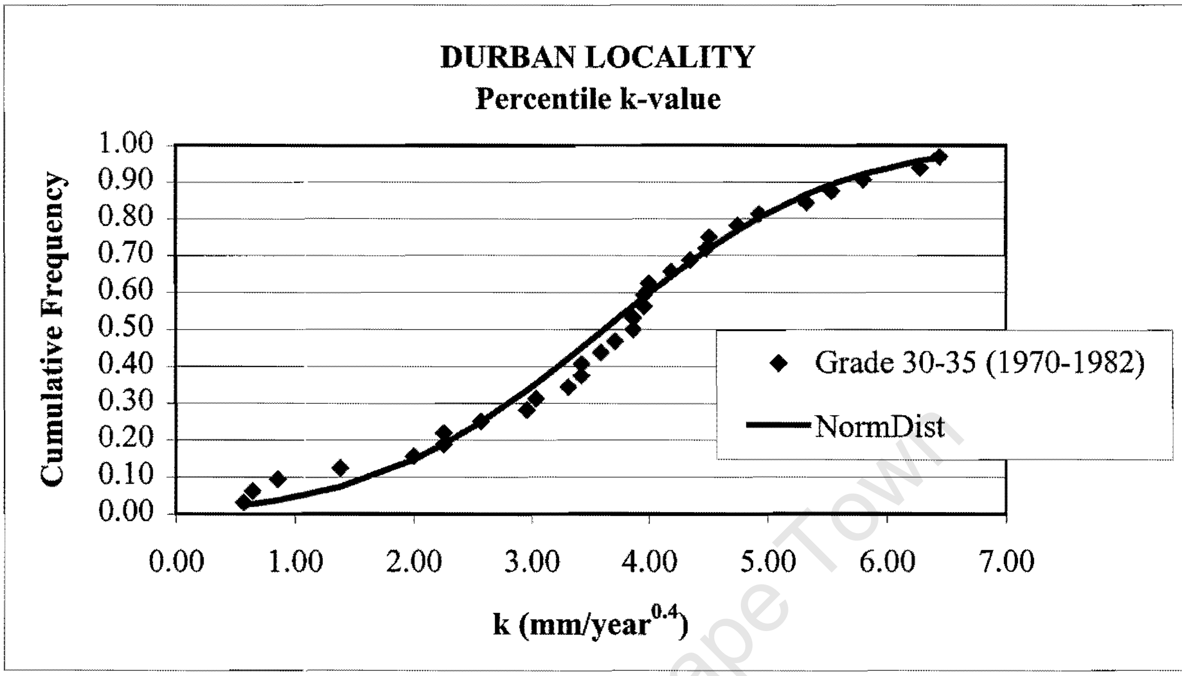
2. Grade 20-25 (Combined Exposed and Sheltered Elements between 1970 - 1982)



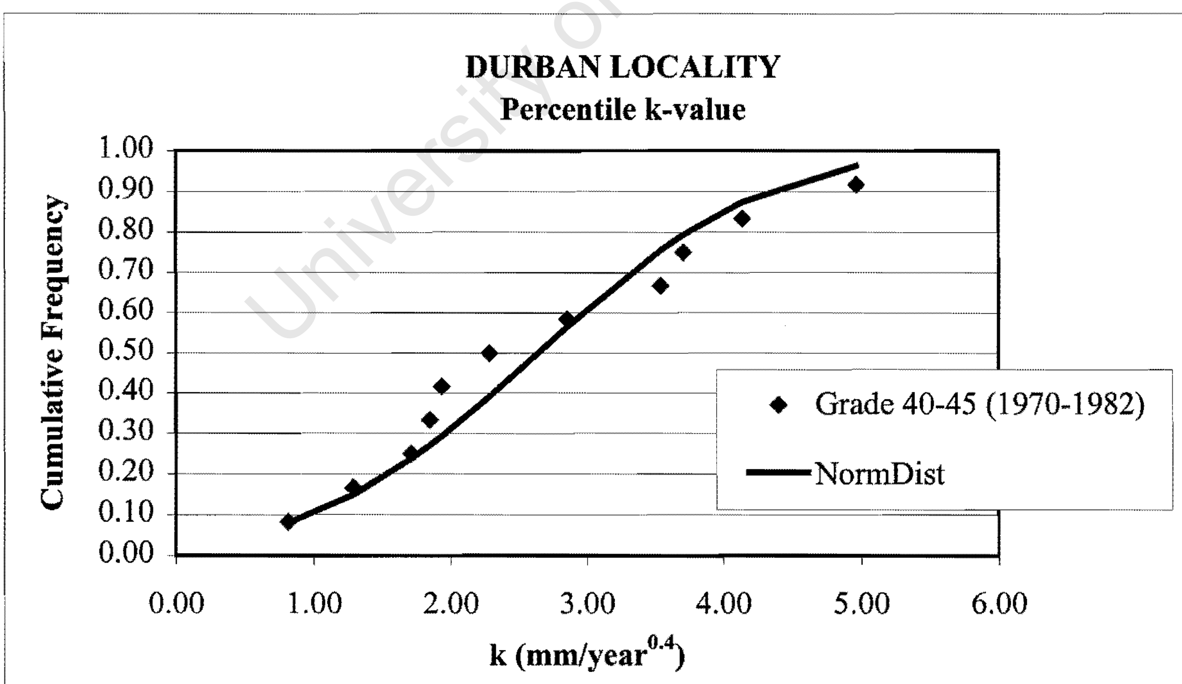
G2. DURBAN LOCALITY

Percentile Carbonation Coefficient (k) Values

3. Grade 30-35 (Combined Exposed and Sheltered Elements between 1970 - 1982)



4. Grade 40-45 (Combined Exposed and Sheltered Elements between 1970 - 1982)



G2. DURBAN LOCALITY

Selected Percentile Carbonation Depth Value

1. Grade 20-25 Concrete (1956 - 1964)

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 1.98)	(k = 2.34)	(k = 3.08)	(k = 3.80)	(k = 4.18)
0	0	0	0	0	0
10	5	6	8	10	10
20	7	8	10	13	14
30	8	9	12	15	16
40	9	10	13	17	18
50	9	11	15	18	20
60	10	12	16	20	21

2. Grade 20-25 Concrete (1970 - 1982)

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 2.85)	(k = 3.56)	(k = 4.97)	(k = 6.35)	(k = 7.01)
0	0	0	0	0	0
10	7	9	12	16	18
20	9	12	16	21	23
30	11	14	19	25	27
40	12	16	22	28	31
50	14	17	24	30	34
60	15	18	26	33	36

G2. DURBAN LOCALITY

Selected Percentile Carbonation Depth Value

3. Grade 30-35 Concrete (1970 - 1982)

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 1.60)	(k = 2.33)	(k = 3.60)	(k = 4.93)	(k = 5.53)
0	0	0	0	0	0
10	4	6	9	12	14
20	5	8	12	16	18
30	6	9	14	19	22
40	7	10	16	22	24
50	8	11	17	24	26
60	8	12	19	25	28

4. Grade 40-45 Concrete (1970 - 1982)

	Percentile Carbonation Depth Values (mm)				
Time	10%	20%	50%	80%	90%
(Years)	(k = 0.94)	(k = 1.53)	(k = 2.65)	(k = 3.71)	(k = 4.38)
0	0	0	0	0	0
10	2	4	7	9	11
20	3	5	9	12	15
30	4	6	10	14	17
40	4	7	12	16	19
50	4	7	13	18	21
60	5	8	14	19	23

BRIDGES IN THE JOHANNESBURG LOCALITY

The Percentile Carbonation Depth Value

Grade 20 - 30 (Exposed and Sheltered Elements Combined)

Age (t)	Grade	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.5}$)	(mm/year$^{0.5}$)		(P<d)	
30	20	15	2.74	1.79	1	0.01	0.02
27	30	14	2.69	1.84	2	0.02	0.02
27	30	10	1.92	1.92	3	0.03	0.03
27	30	18	3.46	1.96	4	0.04	0.03
26	30	20	3.92	2.09	5	0.05	0.04
26	30	28	5.49	2.25	6	0.06	0.06
26	30	14	2.75	2.25	7	0.07	0.06
26	30	10	1.96	2.29	8	0.08	0.06
26	30	16	3.14	2.29	9	0.09	0.06
26	30	15	2.94	2.45	10	0.10	0.08
24	30	15	3.06	2.45	11	0.11	0.08
24	30	20	4.08	2.65	12	0.12	0.12
24	30	20	4.08	2.69	13	0.13	0.13
24	30	20	4.08	2.71	14	0.14	0.13
21	30	13	2.84	2.71	15	0.15	0.13
21	30	15	3.27	2.71	16	0.16	0.13
20	30	8	1.79	2.71	17	0.17	0.13
20	30	20	4.47	2.74	18	0.17	0.14
20	30	24	5.37	2.75	19	0.18	0.14
20	30	23	5.14	2.84	20	0.19	0.16
19	30	19	4.36	2.92	21	0.20	0.19
19	30	19	4.36	2.92	22	0.21	0.19
19	30	17	3.90	2.92	23	0.22	0.19
22	25	18	3.84	2.92	24	0.23	0.19
22	25	19	4.05	2.94	25	0.24	0.19
23	25	21	4.38	3.02	26	0.25	0.22
23	25	17	3.54	3.06	27	0.26	0.23
23	25	19	3.96	3.13	28	0.27	0.25
23	25	21	4.38	3.13	29	0.28	0.25
23	25	21	4.38	3.14	30	0.29	0.25
23	25	14	2.92	3.20	31	0.30	0.27
23	25	11	2.29	3.21	32	0.31	0.28
23	25	18	3.75	3.21	33	0.32	0.28
23	25	10	2.09	3.27	34	0.33	0.30
23	25	18	3.75	3.29	35	0.34	0.30
23	25	24	5.00	3.34	36	0.35	0.32
28	25	16	3.02	3.34	37	0.36	0.32
28	25	17	3.21	3.46	38	0.37	0.37
23	25	15	3.13	3.54	39	0.38	0.40
23	25	25	5.21	3.54	40	0.39	0.40
28	25	14	2.65	3.54	41	0.40	0.40

BRIDGES IN THE JOHANNESBURG LOCALITY

The Percentile Carbonation Depth Value

Grade 20 - 30 (Exposed and Sheltered Elements Combined) (Con't)

Age (t)	Grade	d_c	k	k (sorted)	Rank	Probability	NormDist
(Years)	(MPa)	(mm)	(mm/year$^{0.5}$)	(mm/year$^{0.5}$)		(P<d)	
28	25	17	3.21	3.59	42	0.41	0.42
23	25	13	2.71	3.71	43	0.42	0.47
23	30	23	4.80	3.75	44	0.43	0.49
23	30	18	3.75	3.75	45	0.44	0.49
23	30	18	3.75	3.75	46	0.45	0.49
23	30	26	5.42	3.75	47	0.46	0.49
23	30	25	5.21	3.75	48	0.47	0.49
23	30	24	5.00	3.75	49	0.48	0.49
23	30	24	5.00	3.75	50	0.49	0.49
23	30	22	4.59	3.75	51	0.50	0.49
28	30	30	5.67	3.75	52	0.50	0.49
28	30	26	4.91	3.78	53	0.51	0.50
28	30	23	4.35	3.84	54	0.52	0.52
23	30	11	2.29	3.88	55	0.53	0.54
30	20	18	3.29	3.90	56	0.54	0.55
24	30	9	1.84	3.92	57	0.55	0.56
24	30	11	2.25	3.96	58	0.56	0.57
24	30	12	2.45	3.96	59	0.57	0.57
24	30	11	2.25	4.05	60	0.58	0.61
24	30	12	2.45	4.08	61	0.59	0.62
24	30	25	5.10	4.08	62	0.60	0.62
24	30	20	4.08	4.08	63	0.61	0.62
24	30	19	3.88	4.08	64	0.62	0.62
21	30	17	3.71	4.16	65	0.63	0.65
21	30	20	4.36	4.17	66	0.64	0.66
22	35	15	3.20	4.35	67	0.65	0.72
23	35	14	2.92	4.36	68	0.66	0.72
23	35	16	3.34	4.36	69	0.67	0.72
23	35	18	3.75	4.36	70	0.68	0.73
23	35	14	2.92	4.38	71	0.69	0.73
23	35	15	3.13	4.38	72	0.70	0.73
23	35	16	3.34	4.38	73	0.71	0.73
23	35	13	2.71	4.38	74	0.72	0.73
23	35	23	4.80	4.38	75	0.73	0.73
23	35	21	4.38	4.38	76	0.74	0.73
23	35	23	4.80	4.47	77	0.75	0.76
28	35	19	3.59	4.54	78	0.76	0.78
28	35	20	3.78	4.59	79	0.77	0.80
23	30	23	4.80	4.59	80	0.78	0.80
23	30	23	4.80	4.59	81	0.79	0.80
23	30	13	2.71	4.80	82	0.80	0.85

BRIDGES IN THE JOHANNESBURG LOCALITY

The Percentile Carbonation Depth Value

Grade 20 - 30 (Exposed and Sheltered Elements Combined) (Con't)

Age (t) (Years)	Grade (MPa)	d_c (mm)	k ($mm/year^{0.5}$)	k (sorted) ($mm/year^{0.5}$)	Rank	Probability (P<d)	NormDist
23	30	17	3.54	4.80	83	0.81	0.85
23	30	18	3.75	4.80	84	0.82	0.85
23	30	20	4.17	4.80	85	0.83	0.85
23	30	21	4.38	4.80	86	0.83	0.85
23	30	24	5.00	4.80	87	0.84	0.85
23	30	18	3.75	4.91	88	0.85	0.88
23	30	18	3.75	5.00	89	0.86	0.90
23	30	18	3.75	5.00	90	0.87	0.90
23	30	26	5.42	5.00	91	0.88	0.90
28	35	22	4.16	5.00	92	0.89	0.90
28	35	24	4.54	5.10	93	0.90	0.91
23	30	23	4.80	5.14	94	0.91	0.92
23	35	19	3.96	5.21	95	0.92	0.93
23	35	22	4.59	5.21	96	0.93	0.93
23	30	17	3.54	5.37	97	0.94	0.95
23	30	14	2.92	5.42	98	0.95	0.95
22	30	26	5.54	5.42	99	0.96	0.95
23	30	21	4.38	5.49	100	0.97	0.96
23	30	22	4.59	5.54	101	0.98	0.97
23	30	13	2.71	5.67	102	0.99	0.97
			Average	**3.78**			
			Std. Dev.	**0.97**			

Note: All strengths are assumed strengths

Grade 35 (Exposed Elements)

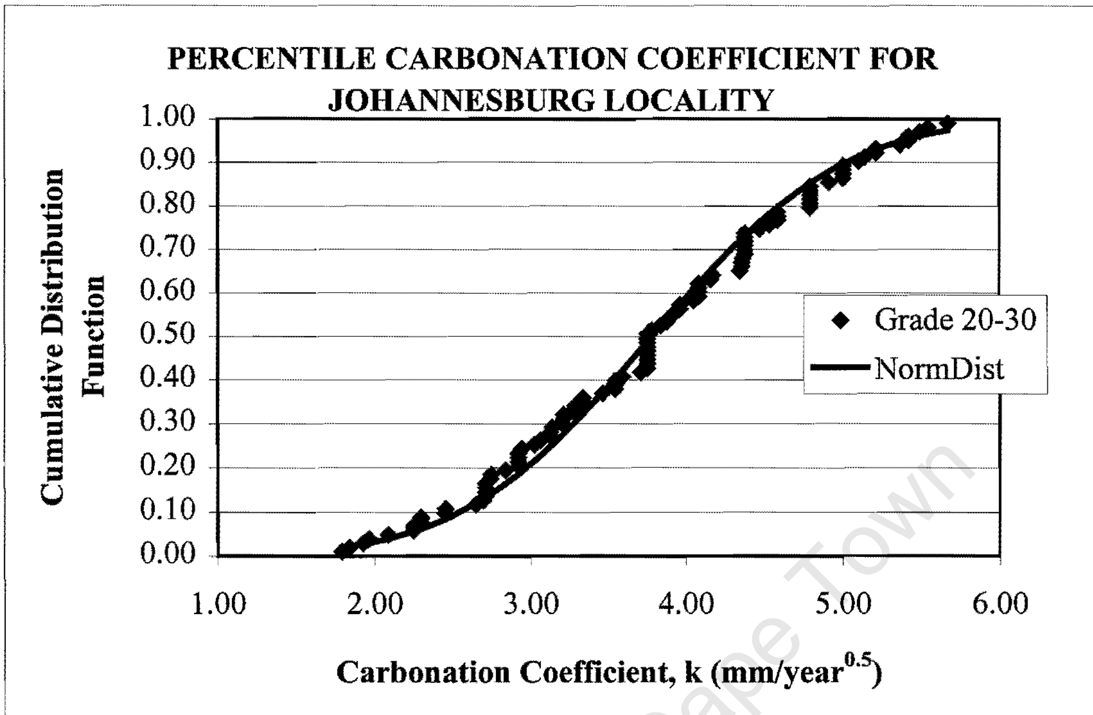
Age (t) (Years)	Grade (MPa)	d_c (mm)	k ($mm/year^{0.5}$)	k (sorted) ($mm/year^{0.5}$)	Rank	Probability (P<d)	NormDist
22	35	23	4.90	2.09	1	0.08	0.15
23	35	17	3.54	2.27	2	0.17	0.19
23	35	23	4.80	2.29	3	0.25	0.20
23	35	10	2.09	2.29	4	0.33	0.20
23	35	23	4.80	2.65	5	0.42	0.30
23	35	11	2.29	2.83	6	0.50	0.36
23	35	11	2.29	3.21	7	0.58	0.49
28	35	15	2.83	3.54	8	0.67	0.61
28	35	17	3.21	4.80	9	0.75	0.92
28	35	14	2.65	4.80	10	0.83	0.92
28	35	12	2.27	4.90	11	0.92	0.93
			Average	**3.24**			
			Std. Dev.	**1.11**			

Note: All strengths are assumed strengths

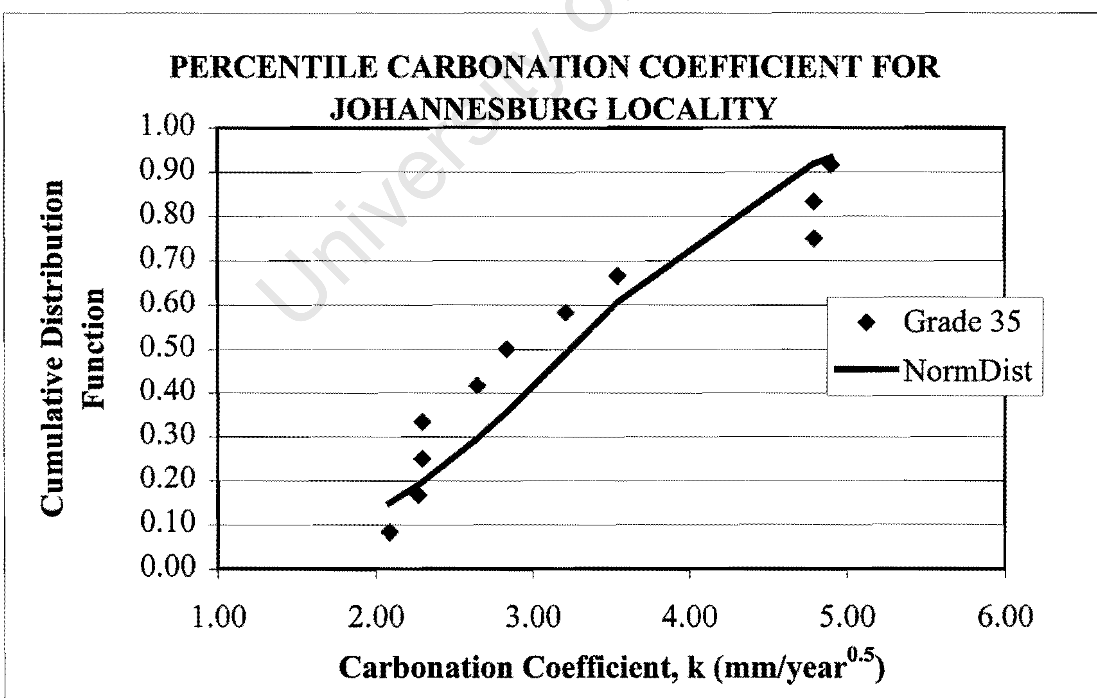
JOHANNESBURG LOCALITY

Percentile Carbonation Coefficient (k) values for Grade 20-30 Concretes

1. Grade 20 - 30 (Exposed and Sheltered Elements Combined)



2. Grade 35 (Exposed Elements)



Johannesburg Locality

Selected Percentile Carbonation Depth Value

1. Grade 20-30 Concrete (Combined Exposed and Sheltered Elements)

	Percentile Carbonation Depth Values (mm)				
Time	**10%**	**20%**	**50%**	**80%**	**90%**
(Years)	**(k = 2.56)**	**(k = 2.97)**	**(k = 3.78)**	**(k = 4.59)**	**(k = 5.00)**
0	0	0	0	0	0
10	8	9	12	15	16
20	11	13	17	21	22
30	14	16	21	25	27
40	16	19	24	29	32
50	18	21	27	32	35
60	20	23	29	36	39

2. Grade 35 Concrete (Exposed Elements)

	Percentile Carbonation Depth Values (mm)				
Time	**10%**	**20%**	**50%**	**80%**	**90%**
(Years)	**(k = 1.83)**	**(k = 2.29)**	**(k = 3.24)**	**(k = 4.32)**	**(k = 4.65)**
0	0	0	0	0	0
10	6	7	10	14	15
20	8	10	14	19	21
30	10	13	18	24	25
40	12	14	20	27	29
50	13	16	23	31	33
60	14	18	25	33	36